2.1 Earth stations operating with geostationary space stations

For an earth station operating with a geostationary space station, the value of G_t and G_r towards the horizon is considered to be constant with time. The percentage of time associated with L_b in equation (1) is the same as the time percentage, p, associated with $P_r(p)$. When determining the coordination area between a coordinating earth station operating to a geostationary space station and terrestrial systems, the coordination distance on any azimuth is the greater of the propagation mode (1) and propagation mode (2) required distances. The required distances for propagation mode (1) and propagation mode (2) are determined using the procedures described in § 2.1.1 and § 2.1.2 respectively, after taking into consideration the following discussion on station-keeping.

When the north/south station-keeping of a geostationary space station is relaxed, the orbit of the space station becomes inclined with an inclination that increases gradually with time. This movement of the space station from its nominal position may require small corresponding adjustments in the elevation angle of the earth station antenna beam. Hence, to avoid considering the time variation in antenna gain in the direction of the horizon, the coordination area of an earth station operating to a space station in a slightly inclined geostationary orbit is determined for the minimum angle of elevation and the associated azimuth at which the space station is visible to the earth station (see Annex 3).

2.1.1 Determination of the coordinating earth station's propagation mode (1) contour

Determination of the propagation mode (1) contour is based on great circle propagation mechanisms and it is assumed, for the interference path, that all the terrestrial stations are pointing directly at the coordinating earth station's location. The required distance, on each azimuth, for propagation mode (1) is that distance which will result in a value of propagation mode (1) predicted path loss that is equal to the propagation mode (1) minimum required loss, $L_b(p)$ (dB), as defined in § 1.3.

$$L_b(p) = P_t + G_e + G_x - P_r(p) \qquad \text{dB} \qquad (4)$$

where:

P_t and $P_r(p)$: as defined in § 1.3

G_e: gain of the coordinating earth station antenna (dBi) towards the horizon at the horizon elevation angle and azimuth under consideration

G_x: maximum antenna gain (dBi) assumed for the terrestrial station. Tables 7 and 8 of Annex 7 give values for G_x for the various frequency bands.

The propagation mode (1) required distance is determined using the procedures described in § 4, and the detailed methods in Annex 1. Specific guidance relevant to the application of the procedures is provided in § 4.4.

2.1.2 Determination of the coordinating earth station's propagation mode (2) contour

The required distance for hydrometeor scatter is that distance that will result in a propagation mode (2) predicted path loss equal to the propagation mode (2) minimum required loss $L(p)$, as defined in equation (3). This propagation mode (2) required distance is determined using the guidance in § 5, and the detailed methods in Annex 2.

For an earth station operating with a geostationary space station having a slightly inclined orbit, the rain-scatter coordination contours for each of the satellite's two most extreme orbit positions are determined individually, using the relevant elevation angles and their associated azimuths to the satellite. The rain scatter area is the total area contained within the two resulting overlapping coordination contours.

2.2 Earth stations operating with non-geostationary space stations

For an earth station that operates with non-geostationary space stations and whose antennas track the space stations, the antenna gain in the direction of the horizon on any azimuth varies with time. The method used to determine the coordination contour is the time invariant gain (TIG) method.

This method uses fixed values of antenna gain based on the maximum assumed variation in horizon antenna gain on each azimuth under consideration. In considering the horizon gain of the antenna for either a transmitting or a receiving earth station, only the horizon antenna gain values during the operational time are to be considered. The horizon antenna gain may be determined using Annex 4. Reference or measured antenna radiation patterns may be used as described in Annex 3. The values of horizon antenna gain defined below are used for each azimuth when applying equation (4) to determine the propagation mode (1) required distances:

$$\begin{aligned} G_e &= G_{max} && \text{for} && (G_{max} - G_{min}) \leq 20\ \text{dB} \\ G_e &= G_{min} + 20 && \text{for} && 20\ \text{dB} < (G_{max} - G_{min}) < 30\ \text{dB} \\ G_e &= G_{max} - 10 && \text{for} && (G_{max} - G_{min}) \geq 30\ \text{dB} \end{aligned} \quad (5)$$

where:

G_e: the gain of the coordinating earth station antenna (dBi) towards the horizon at the horizon elevation angle and azimuth under consideration in equation (4)

G_{max}, G_{min}: maximum and minimum values of the horizon antenna gain (dBi), respectively, on the azimuth under consideration.

The maximum and minimum values of the horizon antenna gain, on the azimuth under consideration, are derived from the antenna pattern and the maximum and minimum angular separation of the antenna main beam axis from the direction of the physical horizon at the azimuth under consideration.

Where a single value of minimum elevation angle for the main beam axis of the earth station antenna is specified for all azimuths, the minimum and maximum values of the horizon gain can be determined, for each azimuth under consideration, from the antenna pattern and the horizon elevation angle at that azimuth. The plot of the horizon elevation angle against azimuth is called the horizon profile of the earth station.

Additional constraints may be included in the determination of the maximum and minimum values of the horizon antenna gain where an earth station is operating with a constellation of non-geostationary satellites at a latitude for which no satellite is visible at the earth station's specified minimum elevation angle over a range of azimuths. Over this range of azimuth angles, the minimum elevation angle of the earth station antenna main beam axis is given by the minimum elevation angle at which any satellite of the constellation is visible at that azimuth. The azimuthal dependence of this minimum satellite visibility elevation angle may be determined from consideration of the orbital altitude and inclination of the satellites in the constellation, without recourse to simulation, using the procedure in § 1.1 of Annex 4. In this case, the horizon antenna gain to be used in the method depends on the profile of the composite minimum elevation angle. This minimum composite elevation angle at any azimuth is the greater of the minimum satellite visibility elevation angle, at the azimuth under consideration, and the specified minimum elevation angle for the earth station which is independent of the azimuth.

Thus, at each azimuth under consideration, the maximum horizon antenna gain will be determined from the minimum value of the angular separation between the earth station horizon profile at this azimuth and the profile of the minimum composite elevation angle. Similarly, the minimum horizon antenna gain will be determined from the maximum value of the angular separation from the earth station horizon profile at this azimuth to the profile of the minimum composite elevation angle. The procedure for calculating the minimum and maximum angular separations from the profile of the minimum composite elevation angle is given in § 1.2 of Annex 4.

The propagation mode (1) required distance is then determined using the procedures described in § 4, and the detailed methods in Annex 1. Specific guidance relevant to the application of the propagation calculations is provided in § 4.4.

3 Determination of the coordination area between earth stations operating in bidirectionally allocated frequency bands

This section describes the procedures to be used for determination of the coordination area for an earth station transmitting in a frequency band allocated to space services in both Earth-to-space and space-to-Earth directions.

There are various coordination scenarios, involving only non-time-varying antenna gains, or only time-varying antenna gains (both earth stations operate to non-geostationary space stations) or, one time-varying antenna gain and one non-time-varying antenna gain.

The following subsections describe the methods for the determination of coordination area which are specific to each of these bidirectional cases. The procedures applicable to the coordination scenario where both earth stations operate with geostationary space stations are given in § 3.1. The other bidirectional coordination scenarios are considered in § 3.2, where particular attention is given to the approaches for using the horizon antenna gain of the receiving earth station for each of the possible coordination scenarios in the appropriate procedure of § 2.

Table 9 of Annex 7 provides the parameters that are to be used in the determination of the coordination area. Table 9 of Annex 7 also indicates whether, in each band, the receiving earth stations operate with geostationary or non-geostationary space stations. In some bands, receiving earth stations may operate with both geostationary and non-geostationary space stations. Table 2 indicates the number of coordination contours which need to be drawn for each coordination scenario and the section(s) containing the applicable calculation methods. Once drawn, each coordination contour must be appropriately labelled.

TABLE 2

Coordination contours required for each bidirectional scenario

Coordinating earth station operating to a space station in the	Unknown receiving earth station operating to a space station in the	Section containing the method to determine G_t and G_r	Contours required	
			No.	Details
Geostationary orbit	Geostationary orbit	§ 3.1	1	A coordination contour comprising both propagation mode (1) and propagation mode (2) contours
	Non-geostationary orbit	§ 3.2.1	1	A propagation mode (1) coordination contour
	Geostationary or non-geostationary orbits[1]	§§ 3.1.1 and 3.2.1	2	Two separate coordination contours, one for the geostationary orbit (propagation mode (1) and mode (2) contours) and one for the non-geostationary orbit (propagation mode (1) contour)
Non-geostationary orbit	Geostationary orbit	§ 3.2.2	1	A propagation mode (1) coordination contour
	Non-geostationary orbit	§ 3.2.3	1	A propagation mode (1) coordination contour
	Geostationary or non-geostationary orbits[1]	§§ 3.2.2 and 3.2.3	2	Two separate propagation mode (1) coordination contours, one for the geostationary orbit and one for the non-geostationary orbit

[1] In this case, the bidirectional frequency band may contain allocations in the Earth-to-space direction for space stations in both the geostationary orbit and non-geostationary orbits. Hence, the coordinating administration will not know whether the unknown receiving earth stations are operating with space stations in the geostationary orbit or non-geostationary orbit.

3.1 Coordinating and unknown earth stations operating with geostationary space stations

When both the coordinating and the unknown earth stations operate with space stations in the geostationary orbit, it is necessary to develop a coordination contour comprising both propagation mode (1) and propagation mode (2) contours, using the procedures described in § 3.1.1 and § 3.1.2, respectively.

3.1.1 Determination of the coordinating earth station's propagation mode (1) contour

The procedure for the determination of the propagation mode (1) contour in this case differs from that described in § 2.2 in two ways. First, the parameters to be used for the unknown receiving earth station are those in Table 9 of Annex 7. Second, and more significantly, the knowledge that both earth stations operate with geostationary satellites can be used to calculate the worst-case value of the horizon antenna gain of the receiving earth station towards the transmitting earth station for each azimuth at the transmitting earth station. The propagation mode (1) required distance is that distance which will result in a value of propagation mode (1) predicted path loss which is equal to the propagation mode (1) minimum required loss, $L_b(p)$ (dB), as defined in § 1.3, and repeated here for convenience.

$$L_b(p) = P_t + G_t + G_r - P_r(p) \quad \text{dB} \tag{6}$$

where:

P_t and $P_r(p)$: are as defined in § 1.3

G_t: gain of the coordinating (transmitting) earth station antenna (dBi) towards the horizon at the horizon elevation angle and the azimuth under consideration

G_r: the horizon antenna gain of the unknown receiving earth station towards the transmitting earth station on the specific azimuth from the coordinating earth station. Values are determined by the procedure in § 2.1 of Annex 5, based on parameters from Table 9 of Annex 7.

To facilitate the determination of the values of G_r to be used at an azimuth from the transmitting earth station, several simplifying approximations must be made:

– that the horizon elevation of the receiving earth station is zero degrees on all azimuths;

– that the receiving earth station operates with a space station that has zero degrees orbital inclination and may be located anywhere on the geostationary orbit that is above the minimum elevation angle, given in Table 9 of Annex 7, for the location of the receiving earth station;

– that the latitude of the receiving earth station is the same as that of the transmitting earth station;

– that plane geometry can be used to interrelate the azimuth angles at the respective earth stations, rather than using the great circle path.

The first three assumptions provide the basis for determining the horizon antenna gain of the receiving earth station on any azimuth. The assumption of 0° horizon elevation angle is conservative since the increase in horizon antenna gain due to a raised horizon would, in practice, be more than offset by any real site shielding[7]. The last two assumptions in the list simplify the calculation of the sum of G_t and G_r along any azimuth. Since the propagation mode (1) required distances are small, in global geometric terms these approximations may introduce a small error in the determination of the horizon antenna gain of the receiving earth station antenna that, in any case, will not exceed 2 dB. Because of the assumption of plane geometry, for a given azimuth at the transmitting earth station the appropriate value of the horizon antenna gain of the receiving earth station is the value on the reciprocal (i.e. ±180°, see § 2.1 of Annex 5) azimuth at the receiving earth station.

The propagation mode (1) required distance is then determined using the procedures described in § 4, and the detailed methods in Annex 1. Specific guidance relevant to the application of the propagation calculations is provided in § 4.4.

3.1.2 Determination of the coordinating earth station's propagation mode (2) contour

The procedure for the determination of the propagation mode (2) contour for a transmitting earth station operating with a geostationary space station uses the same simplifying approximations as made in § 3.1.1, but it is based on a geometrical construction that avoids the requirement for a complex propagation model (see § 3 of Annex 5). Auxiliary contours cannot be used in this method, as the calculations are not based on the propagation mode (2) required loss.

The propagation mode (2) contour is determined using the elevation angle and the azimuth from the coordinating transmitting earth station to the space station, together with the following two considerations:

– the minimum coordination distance (see § 4.2), which will be the required distance for some azimuths; and

– a worst-case required distance determined by the hydrometeor scatter geometry for a receiving earth station located in either of two 6 degree azimuth sectors. Within these sectors, the receiving earth station is assumed to be operating at the minimum elevation angle to a space station in the geostationary orbit and its main beam intersects the beam for the coordinating transmitting earth station at the point where the latter beam passes through the rain height (h_R). Although the scattering can occur anywhere between the coordinating earth station and this point, the intersection of the two beams at this point represents the worst-case interference scenario. Hence, it results in the worst-case distance requirement for receiving earth stations located in the two azimuth sectors.

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[7] While no site shielding can be assumed for the receiving earth station, any site shielding that may exist at the transmitting earth station is considered by taking into account the horizon elevation angle in accordance with § 1 of Annex 1.

For an earth station operating with a space station in an inclined orbit, the lowest expected operational antenna elevation angle and its associated azimuth are used in the calculations.

The propagation mode (2) contour is determined using the method in § 3 of Annex 5.

3.2 Coordinating or unknown earth stations operating with non-geostationary space stations

To determine the coordination area, the method described in § 2.2 is used. For the cases where a coordinating (transmitting) earth station operates with non-geostationary space stations, the following procedures assume that the earth station antenna is tracking the space station, otherwise see § 1.4.2. Table 9 of Annex 7 provides values of horizon antenna gain to be used in the calculations.

One or more of the following three procedures may be needed to determine the required propagation mode (1) coordination contours of Table 2. Propagation mode (2) contours are not required for any of the cases where either of the earth stations operates with space stations in non-geostationary orbits.

3.2.1 A coordinating earth station operating with a geostationary space station with respect to unknown earth stations operating with non-geostationary space stations

When the coordinating earth station operates with a space station in the geostationary orbit and the unknown earth stations operate with space stations in non-geostationary orbits, the propagation mode (1) coordination area is determined using the procedures described in § 2.1.1. The only modification needed is to use the horizon antenna gain (G_r) of the unknown receiving earth station in place of the terrestrial station gain (G_x). The appropriate values for this gain and the appropriate system parameters are contained in Table 9 of Annex 7.

3.2.2 A coordinating earth station operating with non-geostationary space stations with respect to unknown earth stations operating to geostationary space stations

When the coordinating earth station operates to space stations in non-geostationary orbits and the unknown earth stations operate with space stations in the geostationary orbit, the horizon antenna gain (G_r) for the unknown receiving earth station is determined in accordance with the simplifying approximations of § 3.1.1, as elaborated in § 2.1 of Annex 5, and the parameters of Table 9 of Annex 7. Determination of the propagation mode (1) coordination area then follows the procedure of § 2.2 by using the appropriate horizon gain of the receiving earth station at each azimuth under consideration and the appropriate system parameters from Table 9 of Annex 7.

3.2.3 Coordinating and unknown earth stations operating with non-geostationary space stations

When the coordinating earth station operates with space stations in non-geostationary orbits and the unknown earth stations operate with space stations in non-geostationary orbits, the propagation mode (1) coordination area is determined using the procedure described in § 2.2. The only modification is to use the horizon antenna gain (G_r) of the unknown receiving earth station in place of the terrestrial station antenna gain. The appropriate values for this gain and the appropriate system parameters are given in Table 9 of Annex 7.

4 General considerations for the determination of the propagation mode (1) required distance

For the determination of the propagation mode (1) required distances, the applicable frequency range has been divided into three parts. The propagation calculations for the VHF/UHF frequencies between 100 MHz and 790 MHz are based upon propagation mode (1) predicted path loss curves. From 790 MHz to 60 GHz the propagation modelling uses tropospheric scatter, ducting and layer reflection/refraction models. At higher frequencies up to 105 GHz, the model is based on a free-space loss and a conservative assumption for gaseous absorption. The possible range of time percentages is different in the different propagation models.

After taking site shielding (§ 1 of Annex 1) into consideration, for the coordinating earth station only, the following methods are used to determine the propagation mode (1) required distances:

– For frequencies between 100 MHz and 790 MHz, the method described in § 2 of Annex 1.

– For frequencies between 790 MHz and 60 GHz, the method described in § 3 of Annex 1.

– For frequencies between 60 GHz and 105 GHz, the method described in § 4 of Annex 1.

The three methods referred to above rely on a value of propagation mode (1) minimum required loss, determined according to the appropriate system parameters in Tables 7, 8 and 9 of Annex 7.

4.1 Radio-climatic information

For the calculation of the propagation mode (1) required distance, the world has been classified in terms of a radio-meteorological parameter representing clear-air anomalous propagation conditions. The percentage of time β_e for which these clear-air anomalous propagation conditions exist, is latitude dependent and is given by:

$$\beta_e = \begin{cases} 10^{1.67-0.015\zeta_r} & \text{for } \zeta_r \le 70^\circ \quad (7) \\ 4.17 & \text{for } \zeta_r > 70^\circ \quad (8) \end{cases}$$

with:

$$\zeta_r = \begin{cases} |\zeta| - 1.8 & \text{for } |\zeta| > 1.8^\circ \quad (9) \\ 0 & \text{for } |\zeta| \le 1.8^\circ \quad (10) \end{cases}$$

where:

ζ: is the latitude of the earth station's location (in degrees)

For frequencies between 790 MHz and 60 GHz, the path centre sea level surface refractivity (N_0) is used in the propagation mode (1) calculations. This can be calculated using:

$$N_0 = 330 + 62.6\,e^{-\left(\frac{\zeta-2}{32.7}\right)^2} \tag{11}$$

4.2 Minimum coordination distance for propagation modes (1) and (2)

The minimum coordination distance can be calculated in two steps. First calculate distance d_x using:

$$d_x = 100 + \frac{(\beta_e - 40)}{2} \text{ km} \tag{12}$$

where β_e is given in § 4.1.

Then calculate the minimum coordination distance at any frequency f (GHz) in the range 100 MHz to 105 GHz using:

$$d_{min} = \begin{cases} 100 + \frac{(\beta_e - f)}{2} & \text{km} \quad \text{for } f < 40 \text{ GHz} & (13) \\ \frac{(54 - f)d_x + 10(f - 40)}{14} & \text{km} \quad \text{for } 40 \text{ GHz} \le f < 54 \text{ GHz} & (14) \\ 10 & \text{km} \quad \text{for } 54 \text{ GHz} \le f < 66 \text{ GHz} & (15) \\ \frac{10(75 - f) + 45(f - 66)}{9} & \text{km} \quad \text{for } 66 \text{ GHz} \le f < 75 \text{ GHz} & (16) \\ 45 & \text{km} \quad \text{for } 75 \text{ GHz} \le f < 90 \text{ GHz} & (17) \\ 45 - \frac{(f - 90)}{1.5} & \text{km} \quad \text{for } 90 \text{ GHz} \le f \le 105 \text{ GHz} & (18) \end{cases}$$

The distance from which all iterative calculations start (for both propagation mode (1) and propagation mode (2)), is the minimum coordination distance (d_{min}) as given in equations (13) to (18).

4.3 Maximum coordination distance for propagation mode (1)

In the iterative calculation described in Annex 1, it is necessary to set an upper limit (d_{max1}) to the propagation mode (1) coordination distance.

For frequencies less than or equal to 60 GHz and propagation paths entirely within a single Zone, the distance shall not exceed the maximum coordination distance given in Table 3 for that Zone.

For mixed paths, the required distance can comprise one or more contributions from Zones A1, A2, B and C. The aggregate distance for any one zone must not exceed the value given in Table 3. The overall required distance must not exceed the value in Table 3 for the zone in the mixed path having the largest Table 3 value. Thus, a path comprising both Zones A1 and A2 must not exceed 500 km.

TABLE 3

Maximum coordination distances for propagation mode (1) for frequencies below 60 GHz

Zone	d_{max1} (km)
A1	500
A2	375
B	900
C	1 200

For frequencies above 60 GHz, the maximum coordination distance d_{max1} is given by:

$$d_{max\,1} = 80 - 10\log\left(\frac{p}{50}\right) \tag{19}$$

where:

p is defined in § 1.3.

4.4 Guidance on application of propagation mode (1) procedures

As explained in § 1.3, for those cases where earth stations are sharing with terrestrial stations, it is appropriate to apply a correction factor C_i (dB) to the worst case assumptions on system parameters and interference path geometry. This correction factor takes into account the fact that the assumption that all the worst-case values will occur simultaneously is unrealistic when determining the propagation mode (1) required distances.

The characteristics of terrestrial systems depend on the frequency band, and the value of the correction factor to be applied follows the frequency dependence given in equation (20). At frequencies between 100 MHz and 400 MHz, and between 60 GHz and 105 GHz, sharing between earth stations and terrestrial systems is a recent development and there is little established practical experience, or opportunity to analyse operational systems. Hence, the value of the correction factor is 0 dB in these bands. Between 400 MHz and 790 MHz and between 4.2 GHz and 60 GHz, the value of the correction factor is reduced in proportion to the logarithm of the frequency, as indicated in equation (20).

The value of the nominal correction to be used at any frequency f (GHz) is therefore given by:

$$X(f) = \begin{cases} 0 & f \le 0.4 \\ 3.3833X(\log f + 0.3979) & 0.4 < f \le 0.79 \\ X & 0.79 < f \le 4.2 \quad \text{dB} \\ -0.8659X(\log f - 1.7781) & 4.2 < f \le 60 \\ 0 & f > 60 \end{cases} \tag{20}$$

where:

X: 15 dB for a transmitting earth station and 25 dB for a receiving earth station.

In principle, the value of the nominal correction factor, $X(f)$, is distance and path independent. However, there are a number of issues relating to interference potential at the shorter distances, and it is not appropriate to apply the full nominal correction at these distances. The correction factor C_i is therefore applied proportionally with distance along the azimuth under consideration, starting with 0 dB at d_{min}, such that the full value of $X(f)$ is achieved at a nominal distance of 375 km from the earth station.

Hence, the correction is applied using the correction constant $Z(f)$ (dB/km) where

$$Z(f) = \frac{X(f)}{375 - d_{\min}} \quad \text{dB/km} \tag{21}$$

The correction factor C_i (dB) is calculated in equations (1-6b) and (1-31) from the correction constant $Z(f)$ (dB/km).

At distances greater than 375 km, the correction factor C_i to be applied is the value of C_i at 375 km distance.

In addition, the correction factor is applied to its highest value only on land paths. The correction factor is 0 dB for wholly sea paths. A proportion of the correction factor is applied on mixed paths. The amount of correction to be applied to a particular path is determined by the path description parameters used for the propagation mode (1) calculation (correction factors C_i and C_{2i} in § 2 and § 3 respectively of Annex 1). As the correction factor is distance dependent, it is applied automatically within the iterative calculation used to determine the propagation mode (1) required distance (see Annex 1).

The correction factor does not apply to the bidirectional case and therefore in the determination of the bidirectional coordination contour:

$$Z(f) = 0 \text{ dB/km}$$

For the determination of propagation mode (1) auxiliary contours, the propagation mode (1) minimum required loss $L_b(p)$ for p per cent of time in equation (1) (see § 1.3) is replaced by:

$$L_{bq}(p) = L_b(p) + Q \quad \text{dB} \tag{22}$$

where:

Q: auxiliary contour value (dB)

Note that auxiliary contour values are assumed to be negative (i.e. –5, –10, –15, –20 dB, etc.).

5 General considerations for the determination of the propagation mode (2) required distance

The determination of the contour for scattering from hydrometeors (e.g. rain scatter) is predicted on a path geometry that is substantially different from that of the great-circle propagation mechanisms. Hydrometeor scatter can occur where the beams of the earth station and the terrestrial station intersect (partially or completely) at, or below, the rain height h_R (see § 3 of Annex 2). It is assumed that at heights above this rain height the effect of scattering will be suppressed by additional attenuation, and it will not, therefore, contribute significantly to the interference potential. For the determination of the propagation mode (2) contour, it is assumed that the main beam of any terrestrial station exactly intersects the main beam of the coordinating earth station. The mitigating effects of partial beam intersections can be determined using propagation mode (2) auxiliary contours.

Since, to a first approximation, microwave energy is scattered isotropically by rain, interference can be considered to propagate equally at all azimuths around the common volume centred at the beam intersection (see § 1.3). Generally, the beam intersection will not lie on the great-circle path between the two stations. A common volume can therefore result from terrestrial stations located anywhere around the earth station, including locations behind the earth station.

The propagation mode (2) contour is a circle with a radius equal to the propagation mode (2) required distance. Unlike the case for propagation mode (1), the propagation mode (2) contour is not centred on the earth station's physical location, instead it is centred on a point on the earth's surface immediately below the centre of the common volume.

A common volume can exist, with equal probability, at any point along the earth station beam between the earth station's location and the point at which the beam reaches the rain height. To provide appropriate protection for/from terrestrial stations[8], the centre of the common volume is assumed to be half way between the earth station and the point at which its beam intersects the rain height. The distance between the projection of this point on to the earth surface and the location of the earth station is known as Δd (see § 4 of Annex 2). The centre of the propagation mode (2) contour is therefore Δd (km) from the earth station on the azimuth of the earth station's main beam axis.

[8] This procedure does not apply for the case of an earth station sharing a frequency band with other earth stations operating in the opposite direction of transmission, as for that specific case the propagation mode (2) contour is based on a geometric construction.

5.1 The required distance for propagation mode (2)

Propagation mode (2) required distances are measured along a radial originating at the centre of the rain scatter common volume. The calculation requires iteration for distance, starting at the same minimum distance as that defined for propagation mode (1) until either the required propagation mode (2) minimum required loss, or a latitude-dependent propagation mode (2) maximum calculation distance, is achieved. The propagation mode (2) calculations use the method described in Annex 2. The calculations only need to be performed in the frequency range 1 000 MHz to 40.5 GHz. Outside this frequency range, rain scatter interference can be neglected and the propagation mode (2) required distance is set to the minimum coordination distance given by equations (13) to (18).

ANNEX 1

Determination of the required distance for propagation mode (1)

1 Adjustments for earth station horizon elevation angle and distance

For propagation mode (1), the required distance depends on the characteristics of the physical horizon around the earth station. The horizon is characterized by the horizon distance d_h (see below), and the horizon elevation angle ε_h. The horizon elevation angle is defined here as the angle (degrees), viewed from the centre of the earth station antenna, between the horizontal plane and a ray that grazes the physical horizon in the direction concerned. The value of ε_h is positive when the physical horizon is above the horizontal plane and negative when it is below.

It is necessary to determine horizon elevation angles and distances for all azimuths around an earth station. In practice it will generally suffice to do this in azimuth increments of 5°. However, every attempt should be made to identify, and take into consideration, minimum horizon elevation angles that may occur between those azimuths examined in 5° increments.

For the purposes of the determination of the propagation mode (1) required distance it is useful to separate the propagation effects related to the local horizon around the earth station which, on some or all azimuths, may be determined by nearby hills or mountains, from the propagation effects on the remainder of the path. This is achieved by referencing the propagation model to a 0° horizon elevation angle for the coordinating earth station, and then to include a specific term A_h to deal with the known horizon characteristics of the earth station being coordinated. Where appropriate, A_h modifies the value of the path loss, on each azimuth, from which the propagation mode (1) required distance is derived.

There are two situations in which the level of attenuation for the propagation mode (1) path loss with respect to the reference 0° case can change:

– The first is where the coordinating earth station has a positive horizon elevation angle (on a particular azimuth). In this case, it will benefit from additional diffraction propagation losses over the horizon (generally referred to as site shielding). As a result, the attenuation A_h is positive and the value of the required path loss is reduced, with respect to the reference 0° horizon elevation angle case (see equations (1-5a) and (1-5b)).

– The second situation is where the coordinating earth station is at a location above the local foreground, and has a negative (downward) horizon elevation angle on a particular azimuth. In this case, a measure of additional protection is necessary because the path angular distance along the radial is reduced and hence the path loss for a given distance will be lower than for the zero degree elevation angle case. It is convenient to deal with this effect as part of the site shielding calculation. As a result, the attenuation A_h will be negative and the value of the required path loss is increased, with respect to the reference 0° horizon elevation angle case.

The contribution made by the attenuation arising from the coordinating earth station's horizon characteristics to the propagation mode (1) minimum required loss modifies the value of path loss that then needs to be determined in the three propagation mode (1) models. The attenuation A_h is calculated for each azimuth around the coordinating earth station as follows.

The distance of the horizon, d_h, from the earth station's location, is determined by:

$$d_h = \begin{cases} 0.5 \text{ km} & \text{if no information is available about the horizon distance, or if the distance is} < 0.5 \text{ km.} \\ \text{horizon distance (km)} & \text{if this is within the range } 0.5 \text{ km} \le \text{horizon distance} \le 5.0 \text{ km.} \\ 5.0 \text{ km} & \text{if the horizon distance is} > 5.0 \text{ km.} \end{cases}$$

The contribution made by the horizon distance d_h to the total site shielding attenuation is given by A_d (dB) for each azimuth using:

$$A_d = 15\left[1 - \exp\left(\frac{0.5 - d_h}{5}\right)\right]\left[1 - \exp\left(-\varepsilon_h f^{1/3}\right)\right] \quad \text{dB} \qquad (1\text{-}1)$$

where:

f is the frequency (GHz) throughout this Annex.

The total site shielding attenuation along each azimuth from the coordinating earth station is given by:

$$A_h = \begin{cases} 20\log(1 + 4.5\varepsilon_h f^{1/2}) + \varepsilon_h f^{1/3} + A_d & \text{dB} \quad \text{for } \varepsilon_h \ge 0^\circ & (1\text{-}2a) \\ 3[(f+1)^{1/2} - 0.0001f - 1.0487]\varepsilon_h & \text{dB} \quad \text{for } 0^\circ > \varepsilon_h \ge -0.5^\circ & (1\text{-}2b) \\ -1.5[(f+1)^{1/2} - 0.0001f - 1.0487] & \text{dB} \quad \text{for } \varepsilon_h < -0.5^\circ & (1\text{-}2c) \end{cases}$$

The value of A_h must be limited to satisfy the conditions:

$$-10 \le A_h \le (30 + \varepsilon_h) \qquad (1\text{-}3)$$

In equations (1-1), (1-2) and (1-3) the value of ε_h must always be expressed in degrees. The limits defined in equation (1-3) are specified because protection outside these limits may not be realized in practical situations.

2 Frequencies between 100 MHz and 790 MHz

The propagation model given in this section is limited to an average annual time percentage (p) in the range 1% to 50%.

An iterative process is used to determine the propagation mode (1) required distance. First, equation (1-5) is evaluated. Then, commencing at the minimum coordination distance, d_{min}, given by the method described in § 1.5.3 of the main body of this Appendix, equations (1-6) to (1-9) are iterated for distances d_i (where i = 0,1,2,...) incremented in steps of s (km) as described in § 1.3 of the main body of this Appendix. In each iteration, d_i is the distance considered. This process is continued until either of the following expressions becomes true:

$$L_2(p) \geq \begin{cases} L_1(p) & \text{for the main or supplementary contour} \\ L_{1q}(p) & \text{for the auxiliary contour} \end{cases} \tag{1-4a}$$

or:

$$d_i \geq \begin{cases} d_{max1} & \text{for the main or supplementary contour} \\ d_1 & \text{for the auxiliary contour} \end{cases} \tag{1-4b}$$

The required distance, d_1, or the auxiliary contour distance d_q, are then given by the distance for the last iteration: i.e.

$$d_1 = d_i \tag{1-4c}$$

or:

$$d_q = d_i \tag{1-4d}$$

As the eventual mix of zones along a path is unknown, all paths are treated as if they are potential land and sea paths. Parallel calculations are undertaken, the first assuming the path is all land and a second assuming it is all sea. A non-linear interpolation is then performed, the output of which depends upon the current mix of land and sea losses in the distance d_i. Where the current mix along the path includes sections of both warm sea and cold sea zones, all the sea along that path is assumed to be warm sea.

For the main or supplementary contour:

$$L_1(p) = L_b(p) - A_h \tag{1-5a}$$

For an auxiliary contour:

$$L_{1q}(p) = L_{bq}(p) - A_h \tag{1-5b}$$

where:

$L_b(p)$ (dB) and $L_{bq}(p)$ (dB) are the minimum required loss required for p% of the time for the main or supplementary contour and the auxiliary contour with value Q (dB), respectively (see equation (22) in the main body of this Appendix).

Iterative calculations

At the start of each iteration calculate the current distance for i = 0,1,2,...:

$$d_i = d_{\min} + i\,s \tag{1-6a}$$

The correction factor, C_i (dB), (see § 4.4 of the main body of this Appendix) for the distance d_i is given by:

$$C_i = \begin{cases} Z(f)(d_i - d_{min})\ \text{(dB)} & \text{for the main or supplementary contour} \\ 0\ \text{(dB)} & \text{for the auxiliary contour} \end{cases} \tag{1-6b}$$

where $Z(f)$ is given by equation (21) in § 4.4 of the main body of this Appendix.

At distances greater than 375 km, the value of the correction factor (C_i in equation (1-6b)) to be applied is the value of C_i at the 375 km distance.

The loss, $L_{bl}(p)$, where it is assumed that the path is wholly land (Zones A1 or A2), is evaluated successively using:

$$L_{bl}(p) = 142.8 + 20\log f + 10\log p + 0.1 d_i + C_i \tag{1-7}$$

The loss, $L_{bs}(p)$, where it is assumed that the path is wholly cold sea (Zone B) or warm sea (Zone C), is evaluated successively using:

$$L_{bs}(p_l) = \begin{cases} \left.\begin{aligned} &49.91\log(d_i + 1840 f^{1.76}) + 1.195 f^{0.393} (\log p)^{1.38} d_i^{0.597} \\ &\quad + (0.01 d_i - 70)(f - 0.1581) + (0.02 - 2\times 10^{-5} p^2) d_i \\ &\quad\quad + 9.72\ 10^{-9} d_i^2 p^2 + 20.2 \end{aligned}\right\} \text{for Zone (B)} & \text{(1-8a)} \\ \left.\begin{aligned} &49.343\log(d_i + 1840 f^{1.58}) + 1.266(\log p)^{(0.468+2.598 f)} d_i^{0.453} \\ &+ (0.037 d_i - 70)(f - 0.1581) + 1.95\times 10^{-10} d_i^2 p^3 + 20.2 \end{aligned}\right\} \text{for Zone (C)} & \text{(1-8b)} \end{cases}$$

The predicted path loss at the distance considered is then given by:

$$L_2(p) = L_{bs}(p) + \left[1 - \exp\left(-5.5\left(\frac{d_{tm}}{d_i}\right)^{1.1}\right)\right] \cdot (L_{bl}(p) - L_{bs}(p)) \tag{1-9}$$

where:

d_{tm} (km): longest continuous land (inland + coastal) distance, i.e. Zone A1 + Zone A2 along the current path.

3 Frequencies between 790 MHz and 60 GHz

The propagation model given in this section is limited to an average annual time percentage (p) in the range 0.001% to 50%.

An iterative process is used to determine the propagation mode (1) required distance. First, equations (1-11) to (1-21) are evaluated. Then, commencing at the minimum coordination distance, d_{min}, equations (1-22) to (1-32) are iterated for distances d_i, where $i = 0,1,2,...$, incremented in steps of s (km) as described in § 1.3 of the main body of this Appendix. For each iteration, d_i is the distance considered. This process is continued until either of the following expressions becomes true:

$$\begin{cases} (L_5(p) \geq L_3(p)) \text{ and } (L_6(p) \geq L_4(p)) & \text{for the main or supplementary contour} \\ (L_5(p) \geq L_{3q}(p)) \text{ and } (L_6(p) \geq L_{4q}(p)) & \text{for the auxiliary contour} \end{cases} \tag{1-10a}$$

or:

$$d_i \geq \begin{cases} d_{max1} & \text{for the main or supplementary contour} \\ d_1 & \text{for the auxiliary contour} \end{cases} \tag{1-10b}$$

The required distance, d_1, or the auxiliary contour distance, d_q, is then given by the current distance for the last iteration, i.e.

$$d_1 = d_i \tag{1-10c}$$

or:

$$d_q = d_i \tag{1-10d}$$

Specific attenuation due to gaseous absorption

Calculate the specific attenuation (dB/km) due to dry air:

$$\gamma_o = \begin{cases} \left[7.19\times10^{-3} + \dfrac{6.09}{f^2 + 0.227} + \dfrac{4.81}{(f-57)^2 + 1.50}\right] f^2 \times 10^{-3} & \text{for } f \leq 56.77 \text{ GHz} \quad (1\text{-}11a) \\ 10 & \text{for } f > 56.77 \text{ GHz} \quad (1\text{-}11b) \end{cases}$$

The specific attenuation due to water vapour is given as a function of ρ (the water vapour density (g/m^3) by the following equation:

$$\gamma_w(\rho) = \left(0.050 + 0.0021\rho + \frac{3.6}{(f-22.2)^2 + 8.5}\right) f^2 \rho \times 10^{-4} \tag{1-12}$$

Calculate the specific attenuation (dB/km) due to water vapour for the troposcatter propagation model using a water vapour density of 3.0 g/m^3:

$$\gamma_{wt} = \gamma_w(3.0) \tag{1-13a}$$

Calculate the specific attenuation (dB/km) due to water vapour for the ducting propagation model using a water vapour density of 7.5 g/m^3 for paths over land, Zones A1 and A2, using:

$$\gamma_{wdl} = \gamma_w(7.5) \tag{1-13b}$$

Calculate the specific attenuation (dB/km) due to water vapour for the ducting propagation model using a water vapour density of 10.0 g/m^3 for paths over sea, Zones B and C, using:

$$\gamma_{wds} = \gamma_w(10.0) \tag{1-13c}$$

Note that the value of 10 g/m^3 is used for both Zones B and C in view of the lack of data on the variability of water vapour density on a global basis, particularly the minimum values.

Calculate the frequency-dependent ducting specific attenuation (dB/km):

$$\gamma_d = 0.05 f^{1/3} \tag{1-14}$$

For the ducting model:

Calculate the reduction in attenuation arising from direct coupling into over-sea ducts (dB):

$$A_c = \frac{-6}{(1 + d_c)} \tag{1-15}$$

where d_c (km) is the distance from a land based earth station to the coast in the direction being considered.

d_c is zero in other circumstances.

Calculate the minimum loss to be achieved within the iterative calculations:

$$A_1 = 122.43 + 16.5 \log f + A_h + A_c \tag{1-16}$$

For the main or supplementary contour:

$$L_3(p) = L_b(p) - A_1 \tag{1-17a}$$

For an auxiliary contour:

$$L_{3q}(p) = L_{bq}(p) - A_l \tag{1-17b}$$

where:

$L_b(p)$ (dB) and L_{bq} (p) dB are the minimum required loss required for p% of the time for the main or supplementary contour and the auxiliary contour with value Q (dB) respectively (see equation (22) in the main body of this Appendix).

For the tropospheric scatter model:

Calculate the frequency-dependent part of the losses (dB):

$$L_f = 25 \log(f) - 2.5 \left[\log\left(\frac{f}{2} \right) \right]^2 \tag{1-19}$$

Calculate the non-distance-dependent part of the losses (dB):

$$A_2 = 187.36 + 10\varepsilon_h + L_f - 0.15\,N_0 - 10.1\left(-\log\left(\frac{p}{50}\right)\right)^{0.7} \tag{1-20}$$

where:

ε_h: earth station horizon elevation angle in degrees;

N_0: path centre sea level surface refractivity (see equation (11), § 4.1 in the main body of this Appendix).

Calculate the minimum required value for the distance dependent losses (dB):

For the main, or supplementary, contour:

$$L_4(p) = L_b(p) - A_2 \tag{1-21a}$$

For an auxiliary contour:

$$L_{4q}(p) = L_{bq}(p) - A_2 \tag{1-21b}$$

where:

$L_b(p)$ (dB) and $L_{bq}(p)$ (dB): minimum required loss required for p% of the time for the main or supplementary contour and the auxiliary contour of value Q (dB) respectively (see equation (22) in the main body of this Appendix).

Iterative calculations

At the start of each iteration, calculate the distance considered for $i = 0,1,2,...$:

$$d_i = d_{\min} + i\,s \tag{1-22}$$

Calculate the specific attenuation due to gaseous absorption (dB/km):

$$\gamma_g = \gamma_o + \gamma_{wdl}\left(\frac{d_t}{d_i}\right) + \gamma_{wds}\left(1 - \frac{d_t}{d_i}\right) \tag{1-23}$$

where:

d_t (km) is the current aggregate land distance, Zone A1 + Zone A2, along the current path.

Calculate the following zone-dependent parameters:

$$\tau = 1 - \exp\left(-\left(4.12\times10^{-4}\,(d_{lm})^{2.41}\right)\right) \tag{1-24}$$

where:

d_{lm} (km): longest continuous inland distance, Zone A2, along the path considered;

$$\mu_1 = \left[10^{\frac{-d_{tm}}{16-6.6\tau}} + \left[10^{-(0.496+0.354\tau)}\right]^5\right]^{0.2} \tag{1-25}$$

where:

d_{tm} (km): longest continuous land (i.e. inland + coastal) distance, Zone A1 + Zone A2 along the path considered.

μ_1 shall be limited to $\mu_1 \le 1$.

$$\sigma = -0.6 - 8.5\times10^{-9}\,d_i^{3.1}\,\tau \tag{1-26}$$

σ shall be limited to $\sigma \ge -3.4$.

$$\mu_2 = \left(2.48\times10^{-4}\,d_i^2\right)^{\sigma} \tag{1-27}$$

μ_2 shall be limited to $\mu_2 \le 1$.

$$\mu_4 = \begin{cases} 10^{(-0.935+0.0176\,\zeta_r)\log\mu_1} & \text{for } \zeta_r \le 70^\circ \quad (1\text{-}28a) \\ 10^{0.3\log\mu_1} & \text{for } \zeta_r > 70^\circ \quad (1\text{-}28b) \end{cases}$$

where:

ζ_r is given in equations (9) and (10), § 4.1 in the main body of this Appendix.

Calculate the path-dependent incidence of ducting (β) and a related parameter (Γ_1) used to calculate the time dependency of the path loss:

$$\beta = \beta_e\,\mu_1\,\mu_2\,\mu_4 \tag{1-29}$$

where:

β_e is given in equations (7) and (8), § 4.1 in the main body of this Appendix.

$$\Gamma_1 = \frac{1.076}{(2.0058-\log\beta)^{1.012}}\exp\left(-(9.51-4.8\log\beta+0.198(\log\beta)^2)\times10^{-6}\,d_i^{1.13}\right) \tag{1-30}$$

Calculate the correction factor, C_{2i} dB, (see § 4.4 in the main body of this Appendix) using:

$$C_{2i} = \begin{cases} Z(f)(d_i - d_{min})\tau \quad \text{(dB)} & \text{for the main or supplementary contour} \\ 0 \quad \text{(dB)} & \text{for the auxiliary contour} \end{cases} \tag{1-31}$$

where $Z(f)$ is calculated using equation (21) in § 4.4 in the main body of this Appendix.

At distances greater than 375 km the value of the correction factor C_{2i} in equation (1-31) to be applied is the value of C_{2i} at the 375 km distance.

Calculate the distance-dependent part of the losses (dB) for ducting:

$$L_5(p) = (\gamma_d + \gamma_g)d_i + (1.2 + 3.7\times10^{-3} d_i)\log\left(\frac{p}{\beta}\right) + 12\left(\frac{p}{\beta}\right)^{\Gamma_1} + C_{2i} \quad (1\text{-}32)$$

and for tropospheric scatter:

$$L_6(p) = 20\log(d_i) + 5.73\times10^{-4}(112 - 15\cos(2\zeta))d_i + (\gamma_o + \gamma_{wt})d_i + C_{2i} \quad (1\text{-}33)$$

For the determination of distances for auxiliary contours, $C_{2i} = 0$ dB.

4 Frequencies between 60 GHz and 105 GHz

This propagation model is valid for average annual percentage time (p) in the range from 0.001% to 50%.

An iterative process is used to determine the propagation mode (1) required distance. First, equations (1-34) to (1-38) are evaluated. Then commencing at the minimum coordination distance, d_{min}, equations (1-39) and (1-40) are iterated for distances d_i, where i = 0,1,2,..., incremented in steps of s km as described in § 1.3 of the main body of this Appendix. For each iteration, d_i is the distance considered.

This process is continued until either of the following expressions becomes true:

$$L_9(p) \geq \begin{cases} L_8(p) & \text{for the main or supplementary contour} \\ L_{8q}(p) & \text{for the auxiliary contour} \end{cases} \quad (1\text{-}33a)$$

or:

$$d_i \geq \begin{cases} d_{max1} & \text{for the main or supplementary contour} \\ d_1 & \text{for the auxiliary contour} \end{cases} \quad (1\text{-}33b)$$

The required distance, d_1, or the auxiliary contour distance d_q are then given by the current distance for the last iteration: i.e.

$$d_1 = d_i \quad (1\text{-}33c)$$

or:

$$d_q = d_i \quad (1\text{-}33d)$$

Calculate the specific attenuation (dB/km) for dry air in the frequency range 60 GHz to 105 GHz using:

$$\gamma_{om} = \begin{cases} \left[2\times10^{-4}\left(1 - 1.2\times10^{-5} f^{1.5}\right) + \dfrac{4}{(f-63)^2 + 0.936} + \dfrac{0.28}{(f-118.75)^2 + 1.771}\right] f^2\, 6.24\times10^{-4} \text{ dB/km} & \text{for } f > 63.26 \text{ GHz} \quad (1\text{-}34a) \\ 10 \text{ dB/km} & \text{for } f \leq 63.26 \text{ GHz} \quad (1\text{-}34b) \end{cases}$$

Calculate the specific attenuation (dB/km) for an atmospheric water vapour density of 3 g/m^3 using:

$$\gamma_{wm} = \left(0.039 + 7.7 \times 10^{-4} f^{0.5}\right) f^2 2.369 \times 10^{-4} \tag{1-35}$$

Calculate a conservative estimate of the specific attenuation (dB/km) for gaseous absorption using:

$$\gamma_{gm} = \gamma_{om} + \gamma_{wm} \qquad \text{dB/km} \tag{1-36}$$

For the required frequency and the value of earth station site shielding, A_h (dB), as calculated using the method described in § 1 of this Annex, calculate the minimum loss to be achieved in the iterative calculations:

$$L_7(p) = 92.5 + 20\log(f) + A_h \qquad \text{dB} \tag{1-37}$$

For the main or supplementary contour:

$$L_8(p) = L_b(p) - L_7 \qquad \text{dB} \tag{1-38a}$$

For an auxiliary contour:

$$L_{8_q}(p) = L_{b_q}(p) - L_7 \qquad \text{dB} \tag{1-38b}$$

where:

$L_b(p)$ (dB) and $L_{bq}(p)$ (dB) are the minimum required loss required for p% of the time for the main or supplementary contour and the auxiliary contour of value Q (dB) respectively (see equation (22) in the main body of this Appendix).

Iterative calculations

At the start of each iteration calculate the distance for $i = 0,1,2, \ldots$:

$$d_i = d_{\min} + i\,s \tag{1-39}$$

Calculate the distance-dependent losses for the distance:

$$L_9(p) = \gamma_{gm} d_i + 20\log(d_i) + 2.6\left[1 - \exp\left(\frac{-d_i}{10}\right)\right]\log\left(\frac{p}{50}\right) \tag{1-40}$$

For frequencies above 60 GHz, the correction factor (see § 4.4 in the main body of this Appendix) is 0 dB. Therefore, no correction term has been added to equation (1-40).

ANNEX 2

Determination of the required distance for propagation mode (2)

1 Overview

The algorithm given below allows propagation mode (2) path loss, $L_r(p)$ (dB), to be obtained as a monotonic function of rainfall rate, $R(p)$ (mm/h), and with the hydrometeor scatter distance, r_i (km), as a parameter. The model is valid for average annual time percentage (p) in the range 0.001 to 10%. The procedure to determine the hydrometeor scatter contour is as follows:

a) The value of $R(p)$, is determined for the appropriate rain climatic Zones A to Q.

b) Values of $L_r(p)$, are then calculated for incremental values of r_i, starting at the minimum coordination distance d_{min}, in steps of s (km), as described in § 1.3 of the main body of this Appendix. The correct value of r_i is that for which the corresponding value of $L_r(p)$ equals or exceeds the propagation mode (2) minimum required loss L(p). This value of r_i is the propagation mode (2) required distance and is denoted d_r.

c) If the iterative calculation results in r_i equalling or exceeding the appropriate maximum calculation distance (d_{max2}) given in § 2, then the calculation is terminated and d_r is assumed to be equal to d_{max2}. Hence the iteration stops when either of the following expressions becomes true:

$$L_r(p) \geq L(p) \tag{2-1a}$$

or:

$$r_i \geq d_{\max 2} \tag{2-1b}$$

d) The contour for propagation mode (2) is a circle of radius d_r (km) centred on a point along the azimuth of the earth station antenna main beam at a horizontal distance of Δd (km) from the earth station.

2 Maximum calculation distance

As discussed in § 1.5.3 of the main body of this Appendix, it is necessary to set upper limits to the maximum distance used in the iterative calculation of the required distance. The maximum calculation distance to be used for propagation mode (2) (d_{max2}) is latitude dependent and is given in the following equation:

$$d_{max2} = \sqrt{17\,000(h_R + 3)} \text{ km}$$

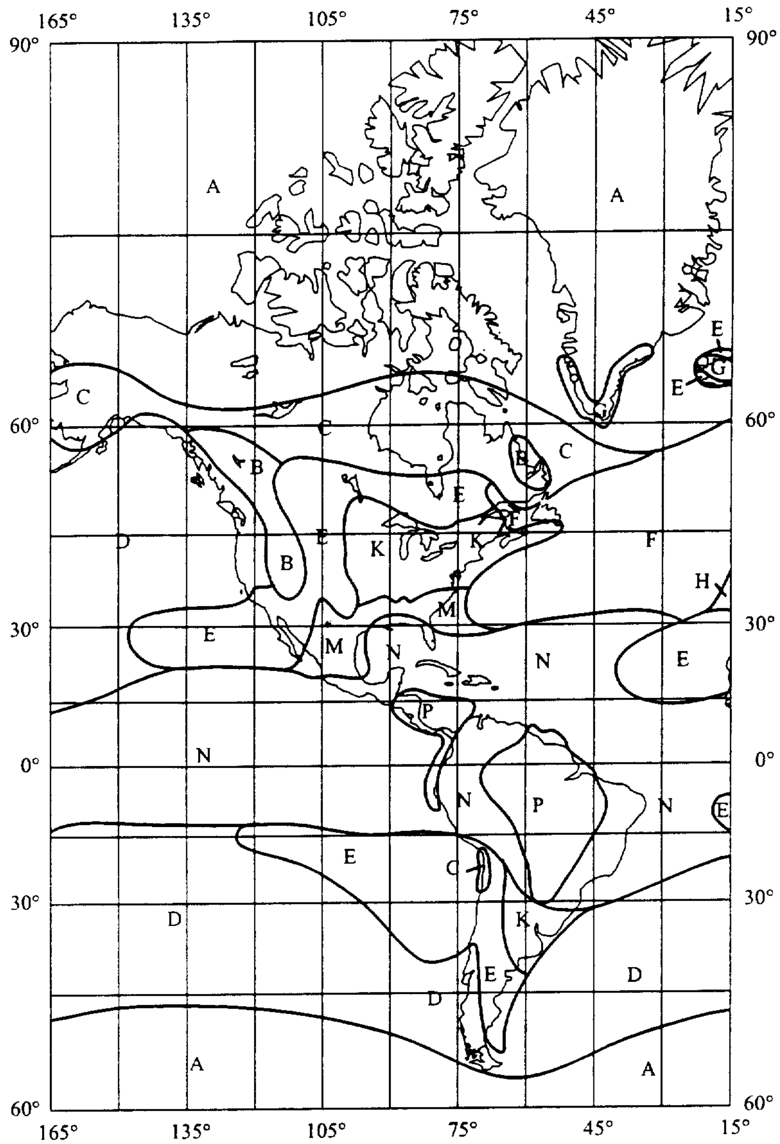
where:

h_R is defined in equations (2-13) and (2-14).

3 Calculation of the propagation mode (2) contour

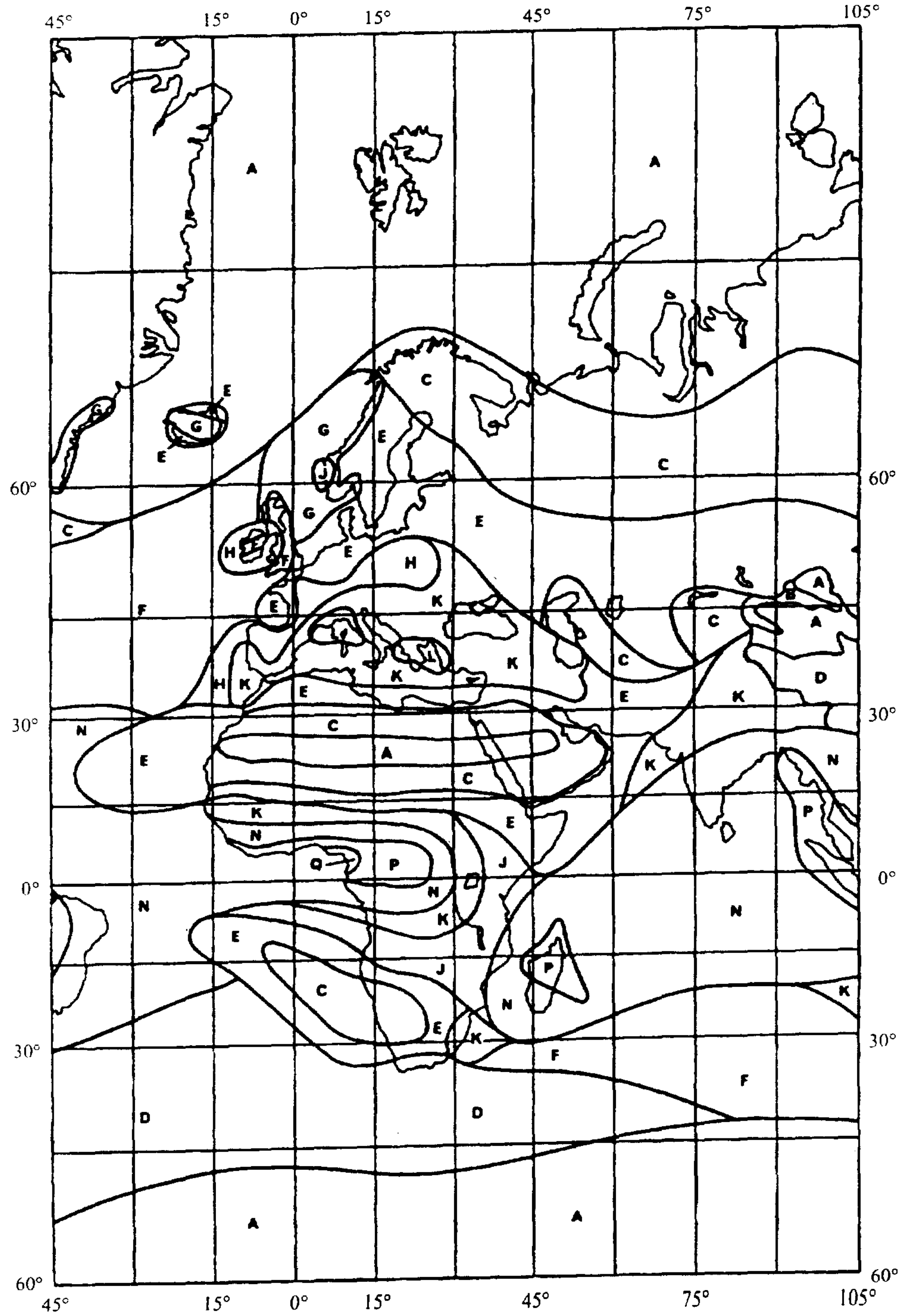
Determine $R(p)$, the rainfall rate (mm/h) exceeded on average for p% of a year. The world has been divided into a number of rain climatic zones (see Figures 2-1, 2-2 and 2-3) which show different precipitation characteristics.

FIGURE 2-1



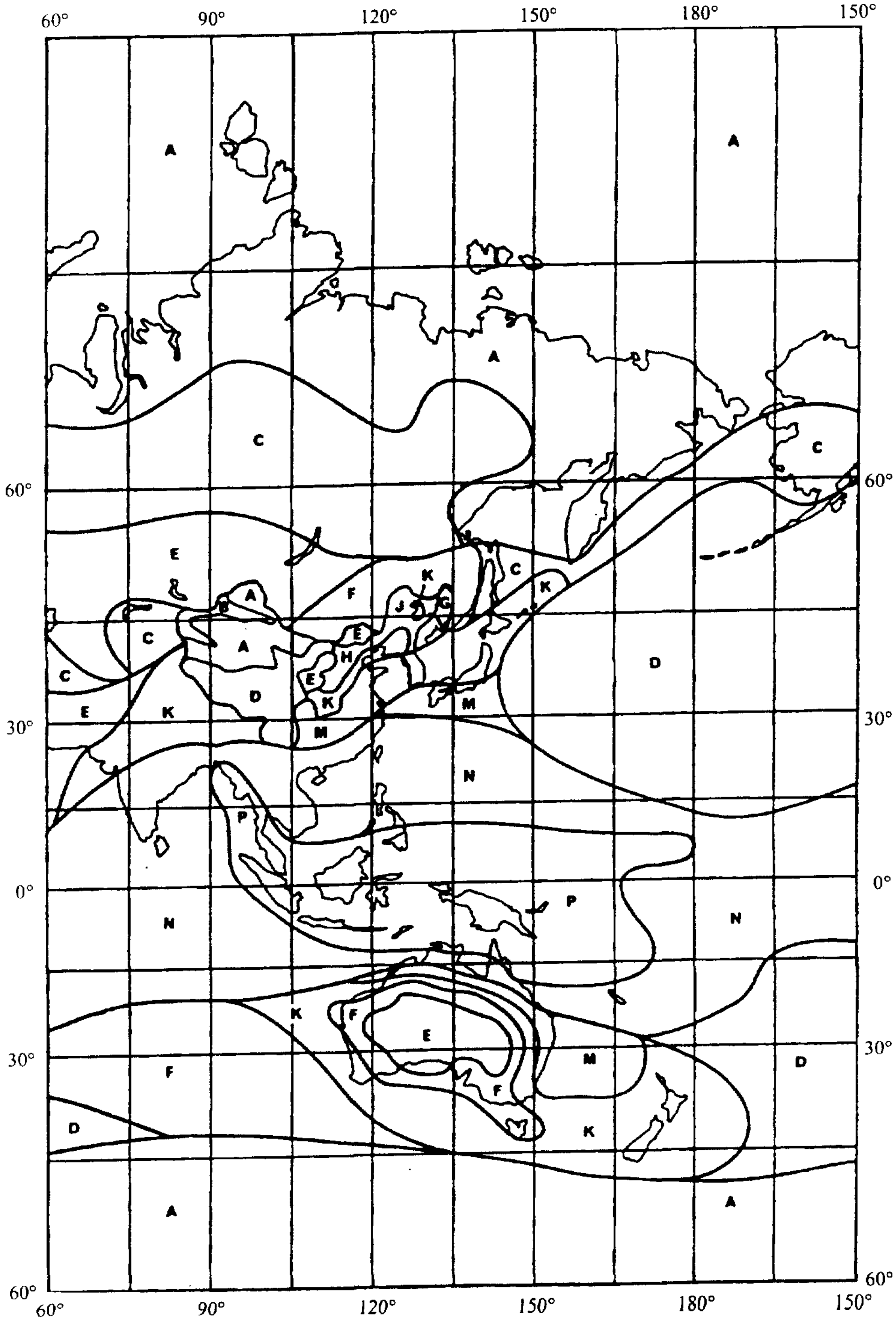
CMR2000/396-021

FIGURE 2-2



CMR2000/396-022

FIGURE 2-3



CMR2000/396-023

The curves shown in Figure 2-4 represent consolidated rainfall-rate distributions, each applicable to several of these rain climatic zones.

Determine which rain climatic zone is applicable to the location of the earth station:

– For $0.001\% < p < 0.3\%$ and the applicable rain climatic zone:

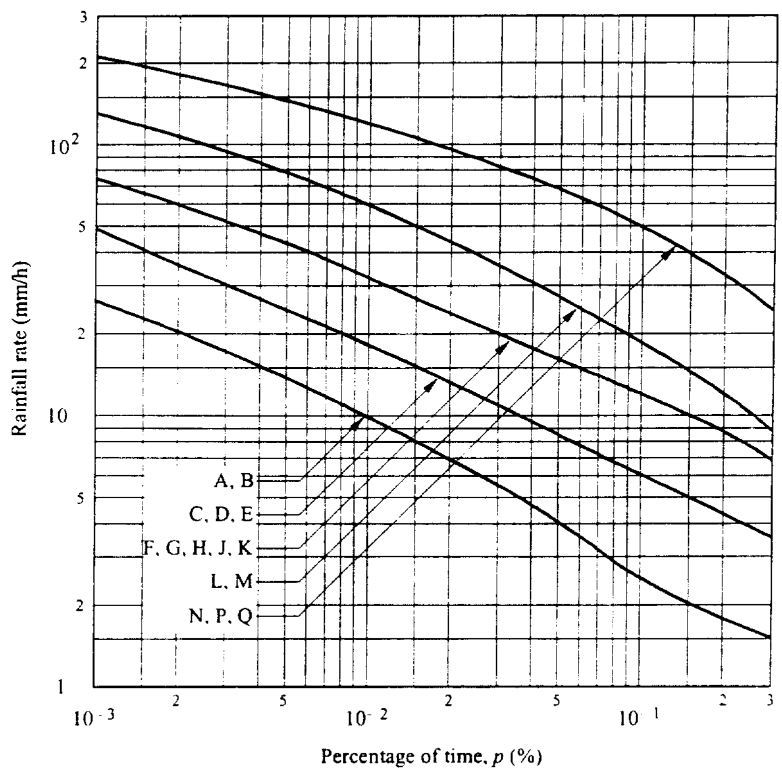
Determine $R(p)$ either from Figure 2-4 or from equations (2-2) to (2-6).

– For $p \geq 0.3\%$:

Use equation (2-7) with values of $R(0.3\%)$ and p_c obtained from Table 4-1.

FIGURE 2-4

Consolidated cumulative distributions of rainfall rate for the rain climatic zones shown in Figures 2-1, 2-2, and 2-3



CMR2000/396-024

Rain climatic Zones A, B

$$R(p) = 1.1p^{-0.465} + 0.25\left[\log(p/0.001)\log^3(0.3/p)\right] - \left[\left|\log(p/0.1)\right| + 1.1\right]^{-2} \tag{2-2}$$

Rain climatic Zones C, D, E

$$R(p) = 2\,p^{-0.466} + 0.5\left[\log(p/0.001)\log^3(0.3/p)\right] \tag{2-3}$$

Rain climatic Zones F, G, H, J, K

$$R(p) = 4.17\,p^{-0.418} + 1.6\left[\log(p/0.001)\log^3(0.3/p)\right] \tag{2-4}$$

Rain climatic Zones L, M

$$R(p) = 4.9\,p^{-0.48} + 6.5\left[\log(p/0.001)\log^2(0.3/p)\right] \tag{2-5}$$

Rain climatic Zones N, P, Q

$$R(p) = 15.6\left(p^{-0.383} + \left[\log(p/0.001)\log^{1.5}(0.3/p)\right]\right) \tag{2-6}$$

TABLE 4

Values of R and p_c for the different rain climatic zones

Rain climatic zone	R (0.3%) (mm/h)	pc (%)
A, B	1.5	2
C, D, E	3.5	3
F, G, H, J, K	7.0	5
L, M	9.0	7.5
N, P, Q	25.0	10

where:

p_c (%): reference time percentage above which the rainfall rate R(p) can be assumed to be zero.

$$R(p) = R(0.3\%)\left[\frac{\log(p_c/p)}{\log(p_c/0.3)}\right]^2 \tag{2-7}$$

Determine the specific attenuation (dB/km) due to rain using values of k and α from Table 5 in equation (2-9). Values of k and α at frequencies other than those in Table 5 can be obtained by interpolation using a logarithmic scale for frequency, a logarithmic scale for k and a linear scale for α.

TABLE 5

Values of k and α for vertical polarization as a function of the frequency

Frequency (GHz)	K	α
1	0.000 0352	0.880
4	0.000 591	1.075
6	0.001 55	1.265
8	0.003 95	1.31
10	0.008 87	1.264
12	0.016 8	1.20
14	0.029	1.15
18	0.055	1.09
20	0.069 1	1.065
22.4	0.090	1.05
25	0.113	1.03
28	0.150	1.01
30	0.167	1.00
35	0.233	0.963
40	0.310	0.929
40.5	0.318	0.926

Let: $$R = R(p) \tag{2-8}$$

Then the specific attenuation (dB/km) due to rain is given by:

$$\gamma_R = k\, R^{\alpha} \tag{2-9}$$

Calculate the effective diameter of the rain cell:

$$d_s = 3.5\, R^{-0.08} \tag{2-10}$$

Then, calculate the effective scatter transfer function:

$$R_{cv} = \frac{2.17}{\gamma_R d_s}\left(1 - 10^{\frac{-\gamma_R d_s}{5}}\right) \tag{2-11}$$

Calculate the additional attenuation outside the common volume:

$$\Gamma_2 = 631 k R^{(\alpha-0.5)} \times 10^{-(R+1)^{0.19}} \tag{2-12}$$

Determine the rain height above ground, h_R (km):

For North America and Europe west of 60° E longitude:

$$h_R = 3.2 - 0.075\ (\zeta - 35) \qquad \text{for} \quad 35 \le \zeta \le 70 \tag{2-13}$$

where:

ζ is the latitude of the coordinating earth station.

For all other areas of the world:

$$h_R = \begin{cases} 5 - 0.075(\zeta - 23) & \text{for } \zeta > 23 \quad \text{northern hemisphere} \quad (2\text{-}14a) \\ 5 & \text{for } 0 \le \zeta \le 23 \quad \text{northern hemisphere} \quad (2\text{-}14b) \\ 5 & \text{for } 0 \ge \zeta \ge -21 \quad \text{southern hemisphere} \quad (2\text{-}14c) \\ 5 + 0.1(\zeta + 21) & \text{for } -71 \le \zeta < -21 \quad \text{southern hemisphere} \quad (2\text{-}14d) \\ 0 & \text{for } \zeta < -71 \quad \text{southern hemisphere} \quad (2\text{-}14e) \end{cases}$$

Determine the specific attenuation due to water vapour absorption (a water vapour density of 7.5 g/m^3 is used):

$$\gamma_{wr} = \left[0.06575 + \frac{3.6}{(f - 22.2)^2 + 8.5}\right] f^2\, 7.5 \times 10^{-4} \tag{2-15}$$

3.1 Iterative calculations

Evaluate equations (2-16) to (2-21) inclusive for increasing values of r_i, where r_i is the current distance considered (km) between the region of maximum scattering and the possible location of a terrestrial station and $i = 0,1,2,...$etc. Continue this process until either of the conditions given in equations (2-1a) and (2-1b) is true. Then the rain-scatter required distance d_r is the current value of r_i.

$$r_i = d_{\min} + i\, s \tag{2-16}$$

Determine the loss above the rain height, L_{ar} (dB), applicable to scatter coupling:

$$L_{ar} = \begin{cases} 6.5\left[6(r_i - 50)^2 \times 10^{-5} - h_R\right] & \text{for } 6(r_i - 50)^2 \times 10^{-5} > h_R \quad (2\text{-}17a) \\ 0 & \text{for } 6(r_i - 50)^2 \times 10^{-5} \le h_R \quad (2\text{-}17b) \end{cases}$$

Calculate the additional attenuation for the departure from Rayleigh scattering:

$$A_b = \begin{cases} 0.005\,(f - 10)^{1.7} R^{0.4} & \text{for } 10 \text{ GHz} < f < 40.5 \text{ GHz} \quad (2\text{-}18a) \\ 0 & \text{for } f \le 10 \text{ GHz or when } L_{ar} \ne 0 \quad (2\text{-}18b) \end{cases}$$

Calculate the effective path length for oxygen absorption:

$$d_0 = \begin{cases} 0.7\, r_i + 32 & \text{for } r_i < 340 \text{ km} \quad (2\text{-}19a) \\ 270 & \text{for } r_i \ge 340 \text{ km} \quad (2\text{-}19b) \end{cases}$$

Calculate the effective path length for water vapour absorption:

$$d_v = \begin{cases} 0.7\, r_i + 32 & \text{for } r_i < 240 \text{ km} \quad (2\text{-}20a) \\ 200 & \text{for } r_i \ge 240 \text{ km} \quad (2\text{-}20b) \end{cases}$$

Determine the propagation mode (2) path loss, L_r (dB):

$$L_r = 168 + 20\log r_i - 20\log f - 13.2\log R - G_x + A_b - 10\log R_{cv} + \Gamma_2 + L_{ar} + \gamma_o d_0 + \gamma_{wr} d_v \qquad (2\text{-}21)$$

where:

γ_o: as given in equation (1-11)

G_x: terrestrial network antenna gain in Tables 7 or 8 of Annex 7.

4 Construction of the propagation mode (2) contour

In order to determine the centre of the circular propagation mode (2) contour, it is necessary to calculate the horizontal distance to this point from the earth station, along the azimuth of the earth station antenna main beam axis. The distance, Δd (km), to the centre of the propagation mode (2) contour is given by:

$$\Delta d = \frac{h_R}{2 \tan \varepsilon_s} \qquad (2\text{-}23)$$

where:

ε_s: earth station antenna main beam axis elevation angle

and

Δd shall be limited to the distance $(d_r - 50)$ km.

The propagation mode (2) required distance d_r must lie within the range between the minimum coordination distance d_{min} and the propagation mode (2) maximum calculation distance d_{max2}.

Draw the propagation mode (2) contour as a circle of radius d_r km around the centre determined above. The propagation mode (2) contour is the locus of points on this circle. However, if any part of the propagation mode (2) contour falls within the contour defined by the minimum coordination distance, this arc of the propagation mode (2) contour is taken to be identical to the contour based on the minimum coordination distance and the propagation mode (2) contour is then no longer circular.

ANNEX 3

Antenna gain towards the horizon for an earth station operating with a geostationary space station

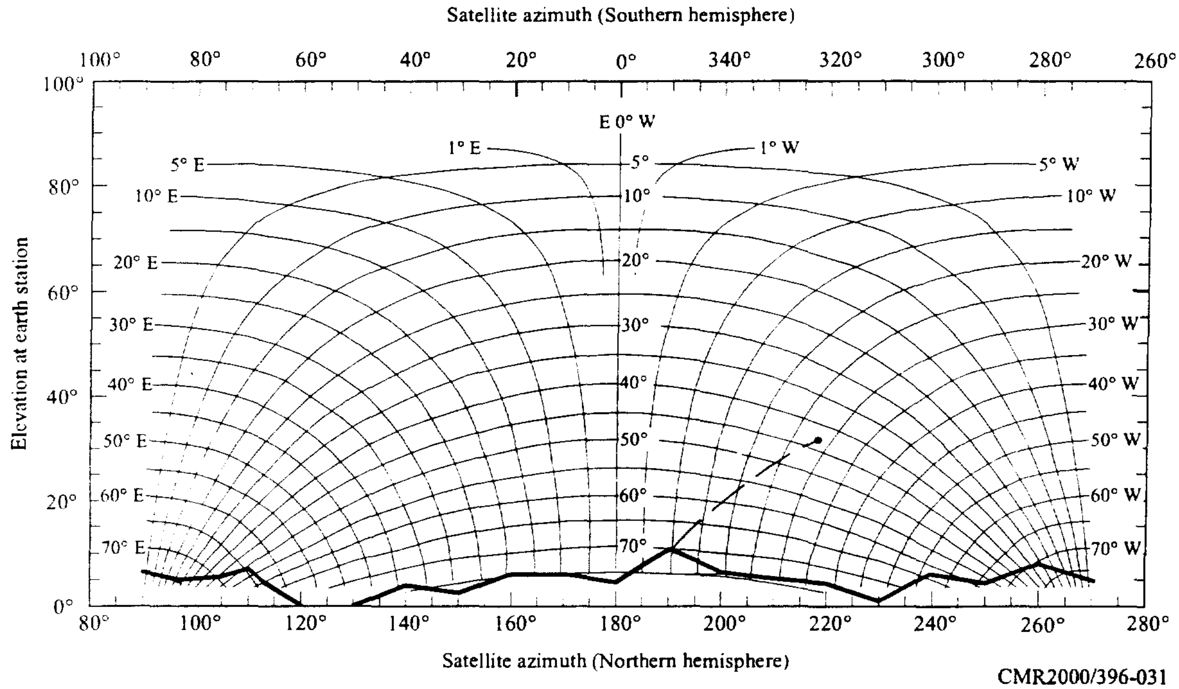
1 General

The gain component of the earth station antenna in the direction of the physical horizon around an earth station is a function of the angular separation between the antenna main beam axis and the horizon in the direction under consideration. When the earth station is used to transmit to a space station in a slightly inclined orbit, all possible pointing directions of the antenna main beam axis need to be considered. For earth station coordination, knowledge of $\varphi(\alpha)$, the minimum possible value of the angular separation that will occur during the operation of the space station, is required for each azimuth.

When a geostationary space station maintains its location close to its nominal orbital position, the earth station's main beam axis elevation angle ε_S and the azimuth angle α_S to the space station from the earth station's latitude ζ are uniquely related. Figure 3-1 shows the possible location arcs of positions of a space station on the geostationary orbit in a rectangular azimuth/elevation plot. It shows arcs corresponding to a set of earth station latitudes and the intersecting arcs correspond to points on the orbit with a fixed difference in longitude East or West of the earth station. Figure 3-1 also shows a portion of the horizon profile $\varepsilon_h(\alpha)$. The off-axis angle $\varphi(\alpha)$ between the horizon profile at an azimuth of 190° and a space station located 28° W of an earth station at 43° N latitude is indicated by the great-circle arc shown dashed on Figure 3-1.

FIGURE 3-1

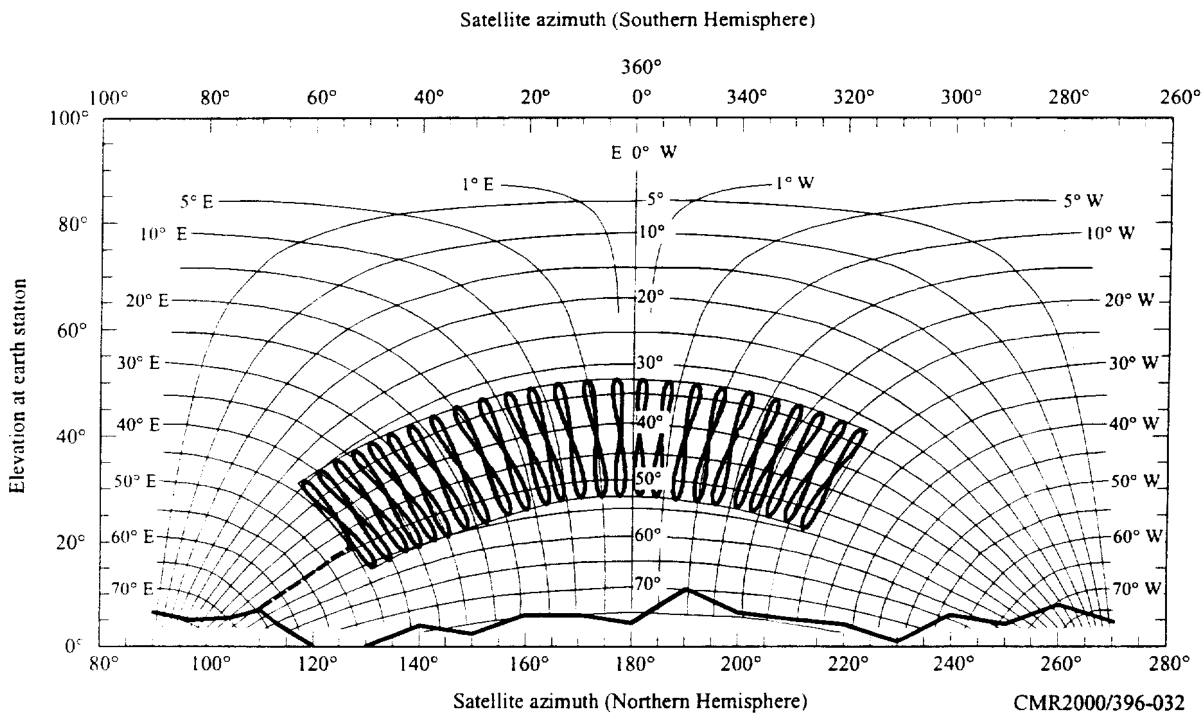
Position arcs of geostationary satellites with horizon and the arc from the horizon at azimuth 190° to a satellite 28° W of an earth station at 43° N latitude



When the north/south station-keeping of a geostationary satellite is relaxed, the orbit of the satellite becomes inclined, with an inclination that increases gradually with time. As viewed from the earth, the position of the satellite traces a figure eight during each 24-hour period. Figure 3-2 shows the variations in the trajectories of a set of satellites, each with 10° inclination, spaced by 3° along the geostationary orbit from 28° W to 44° E, with respect to an earth station at 43° N latitude. Figure 3-2 also shows, with a dashed curve, the great-circle arc corresponding to the minimum off-axis angle $\varphi(\alpha)$ between a point on the trajectory of one of the satellites and the horizon profile at an azimuth of 110°.

FIGURE 3-2

Position arcs of geostationary satellites with horizon and the arc from the horizon at azimuth 110° to satellites with 10° inclination on the geostationary orbital arc from 28° W to 44° E of an earth station at 43° N latitude



For a transmitting earth station operating in a frequency band that is also allocated for bidirectional use by receiving earth stations operating with geostationary space stations, refer to § 2.1 of Annex 5.

2 Determination of the angular separation $\varphi(\alpha)$

For the determination of the off-axis angle $\varphi(\alpha)$, two cases are distinguished. These depend on whether the orbit of the space station has no inclination, or is slightly inclined. The following equations may be used in both of these cases:

$$\psi_s(i,\delta) = \arccos\,(\sin\zeta \sin i + \cos\zeta \cos i \cos\delta \qquad (3\text{-}1)$$

$$\varepsilon_s(i,\delta) = \arcsin\left[\frac{K\cos\psi_s(i,\delta) - 1}{\left(1 + K^2 - 2K\cos\psi_s(i,\delta)\right)^{1/2}}\right] \qquad (3\text{-}2)$$

$$\alpha_{os}(i,\delta) = \arccos\left[\frac{\sin i - \cos\psi_s \sin\zeta}{\sin\psi_s \cos\zeta}\right] \qquad (3\text{-}3)$$

$\alpha_s(i, \delta) = \alpha_{0s}(i, \delta)$ for a space station located east of the earth station ($\delta \geq 0$) (3-4)

$\alpha_s(i, \delta) = 360° - \alpha_{0s}(i, \delta)$ for a space station located west of the earth station ($\delta \leq 0$) (3-5)

$$\varphi(\alpha, i, \delta) = \arccos\left[\cos \varepsilon_h(\alpha) \cos \varepsilon_s(i, \delta) \cos(\alpha - \alpha_s(i, \delta)) + \sin \varepsilon_h(\alpha) \sin \varepsilon_s(i, \delta)\right] \quad (3\text{-}6)$$

where:

ζ: latitude of the earth station (positive for north; negative for south)

δ: difference in longitude between the earth station and a space station

i: latitude of a sub-satellite point (positive for north; negative for south)

$\psi_s(i, \delta)$: great-circle arc between the earth station and a sub-satellite point

$\alpha_s(i, \delta)$: space station azimuth as seen from the earth station

$\varepsilon_s(i, \delta)$: space station elevation angle as seen from the earth station

$\varphi(\alpha, i, \delta)$: angle between the main beam and the horizon direction corresponding to the azimuth (α) under consideration when the main beam is steered towards a space station with a sub-satellite point at latitude i and longitude difference δ

α: azimuth of the direction under consideration

ε_h: elevation angle of the horizon at the azimuth under consideration, α

$\varphi(\alpha)$: angle to be used for horizon gain calculation at the azimuth under consideration, α

K: orbit radius/earth radius, which for the geostationary orbit is assumed to be 6.62.

All arcs mentioned above are in degrees.

Case 1: **Single space station, no orbital inclination**

For a space station operating with no orbital inclination at an orbital position with difference in longitude δ_0, equations (3-1) to (3-6) may be applied directly using $i = 0$ to determine $\varphi(\alpha)$ for each azimuth α. Thus:

$$\varphi(\alpha) = \varphi(\alpha, 0, \delta_0) \quad (3\text{-}7)$$

where:

δ_0: difference in longitude between the earth station and the space station.

Case 2: **Single space station, slightly inclined orbit**

For a space station operating in a slightly inclined orbit on a portion of the geostationary arc with a nominal longitude difference of δ_0, the maximum orbital inclination over its lifetime, i_s, must be considered. Equations (3-1) to (3-6) may be applied to develop the minimum off-axis angle to each of four arcs in azimuth/elevation that bound the trajectory of the space station in angle and elevation. The bounding arcs correspond to the maximum and minimum latitudes of the sub-satellite points and the extremes of the difference in longitude between the earth and space stations when the space station is operating at its maximum inclination.

The determination of the minimum off-axis angles in equations (3-8) to (3-12) may be made by taking increments along a bounding contour. The step size in inclination i or longitude δ should be between 0.5° and 1.0° and the end points of the respective ranges should be included in the calculation.

The horizon profile $\varepsilon_h(\alpha)$ used in the determination of $\varphi(\alpha)$ is specified at increments in azimuth α that do not exceed 5°.

Thus:

$$\varphi(\alpha) = \min_{n=1 \text{ to } 4} \varphi_n(\alpha) \tag{3-8}$$

with:

$$\varphi_1(\alpha) = \min_{\delta_0 - \delta_s \leq \delta \leq \delta_0 + \delta_s} \varphi(\alpha, -i_s, \delta) \tag{3-9}$$

$$\varphi_2(\alpha) = \min_{\delta_0 - \delta_s \leq \delta \leq \delta_0 + \delta_s} \varphi(\alpha, i_s, \delta) \tag{3-10}$$

$$\varphi_3(\alpha) = \min_{-i_s \leq i \leq i_s} \varphi(\alpha, i, \delta_0 - \delta_s) \tag{3-11}$$

$$\varphi_4(\alpha) = \min_{-i_s \leq i \leq i_s} \varphi(\alpha, i, \delta_0 + \delta_s) \tag{3-12}$$

$$\delta_s = (i_s / 15)^2 \tag{3-13}$$

where:

i_s: maximum operational inclination angle of the satellite orbit

δ_s: maximum longitude change from nominal value of the sub-satellite point of a satellite with orbital inclination i_s.

3 Determination of antenna gain

The relationship $\varphi(\alpha)$ is used to derive a function for the horizon antenna gain (dBi), $G(\varphi)$ as a function of the azimuth α, by using the actual earth station antenna pattern, or a formula giving a good approximation. For example, in cases where the ratio between the antenna diameter and the wavelength is equal to or greater than 35, the following equation is used:

$$G(\varphi) = \begin{cases} G_{amax} - 2.5\times10^{-3}\left(\dfrac{D}{\lambda}\varphi\right)^2 & \text{for } 0 < \varphi < \varphi_m \\ G_1 & \text{for } \varphi_m \le \varphi < \varphi_r \\ 29 - 25\log\varphi & \text{for } \varphi_r \le \varphi < 36^\circ \\ -10 & \text{for } 36^\circ \le \varphi \le 180^\circ \end{cases} \qquad (3\text{-}14)$$

$$G_1 = \begin{cases} -1 + 15\log\left(D/\lambda\right) & \text{dBi for } D/\lambda \ge 100 \\ -21 + 25\log\left(D/\lambda\right) & \text{dBi for } 35 \le D/\lambda < 100 \end{cases}$$

$$\varphi_m = \frac{20\lambda}{D}\sqrt{G_{amax} - G_1} \qquad \text{degrees}$$

$$\varphi_r = \begin{cases} 15.85\left(D/\lambda\right)^{-0.6} & \text{degrees} \quad \text{for } D/\lambda \ge 100 \\ 100\left(\lambda/D\right) & \text{degrees} \quad \text{for } 35 \le D/\lambda < 100 \end{cases}$$

Where a better representation of the actual antenna pattern is available, it may be used.

In cases where D/λ is not given, it may be estimated from the expression:

$$20\log\frac{D}{\lambda} \approx G_{amax} - 7.7$$

where:

G_{amax}: main beam axis antenna gain (dBi).

D: antenna diameter (m)

λ: wavelength (m)

G_1: gain of the first side lobe (dBi)

ANNEX 4

Antenna gain toward the horizon for an earth station operating with non-geostationary space stations

This Annex presents methods which may be used to determine the antenna gain towards the horizon for an earth station operating to non-geostationary satellites using the TIG method described in § 2.2 of the main body of this Appendix.

1 Determination of the horizon antenna gain

In its simplest implementation, the TIG method depends on the minimum elevation angle of the beam axis of the earth station antenna (ε_{sys}), which is a system parameter that has the same value on all azimuths from the earth station. If the horizon elevation angle at an azimuth under consideration is ε_h (degrees), the minimum separation angle from the horizon at this azimuth to any possible pointing angle for the main beam axis of the antenna (φ_{min}) is equal to the difference between these two angles ($\varepsilon_{sys} - \varepsilon_h$), but it is not less than zero degrees. The maximum separation angle from the horizon at this azimuth to any possible pointing angle for the main beam axis of the antenna (φ_{max}) is equal to the difference between the sum of these two angles and 180 degrees ($180 - \varepsilon_{sys} - \varepsilon_h$). The maximum and minimum values of horizon gain for the azimuth under consideration are obtained from the gain pattern of the earth station antenna at these off-axis angles. Where no pattern is available the pattern of § 3 of Annex 3 may be used.

Additional constraints may be included in the determination of the maximum and minimum values of horizon antenna gain where an earth station operates with a constellation of non-geostationary satellites that are not in near-polar orbit. In this case, depending on the latitude of the earth station, there may be portions of the hemisphere above the horizontal plane at the earth station in which no satellite will appear. To include these visibility limitations within this method, it is first necessary to determine, for a closely spaced set of azimuth angles around the earth station, the minimum elevation angle at which a satellite may be visible. This minimum satellite visibility elevation angle (ε_v) may be determined from consideration of the visibility of the edge of the shell formed by all possible orbits having the orbital inclination and altitude of the satellites in the constellation.

The lowest elevation angle towards which the main-beam axis of the earth station antenna will point on any azimuth is the minimum composite elevation angle (ε_c), which is equal to the greater of the minimum satellite visibility elevation angle (ε_v) and the minimum elevation angle of the earth station (ε_{sys}). After the minimum composite elevation angle has been determined for all azimuths by the procedure of § 1.1 of this Annex, the resulting profile of the minimum composite elevation angles can be used, in the procedure of § 1.2 of this Annex, to determine the maximum and minimum values of horizon gain at any azimuth.

Further information and an example of this method may be found in the latest version of Recommendation ITU-R SM.1448.

1.1 Determination of satellite visibility limits

The visibility limits of a constellation of satellites can be determined from the inclination angle of the most inclined satellite and the altitude of the lowest satellite in the constellation. For this determination, six cases may be distinguished, but not all of these may be applicable for a given constellation and a given earth station latitude. The azimuth and the corresponding lower limit on the elevation angle are developed by a parametric method using a set of points on the edge of the orbital shell of the constellation. The approach is to develop this relationship for azimuths to the east of a station in the northern hemisphere. Elevation angles for azimuths to the west of the station and for all azimuths for stations in the southern hemisphere are obtained by symmetry. The following equations, which are applicable to circular orbits only, may be used for the complete determination of the horizon antenna gain in all practical cases:

$$\psi(\delta) = \arccos\left(\sin\zeta_e \sin i_s + \cos\zeta_e \cos i_s \cos\delta\right) \tag{4-1}$$

$$\varepsilon_v(\delta) = \arcsin\left[\frac{K_1\cos[\psi(\delta)] - 1}{\left(1 + K_1^2 - 2K_1\cos[\psi(\delta)]\right)^{1/2}}\right] \tag{4-2}$$

$$\alpha_0(\delta) = \arccos\left[\frac{\sin i_s - \cos[\psi(\delta)]\ \sin\zeta_e}{\sin[\psi(\delta)]\ \cos\zeta_e}\right] \tag{4-3}$$

with

$$\alpha(\delta) = \begin{cases} \alpha_0(\delta) \text{ and} & \\ 360 - \alpha_0(\delta) & \text{for earth stations north of the Equator} \\ 180 - \alpha_0(\delta) \text{ and} & \\ 180 + \alpha_0(\delta) & \text{for earth stations south of the Equator} \end{cases} \tag{4-4}$$

where:

- i_s: orbital inclination of the satellites in the constellation assumed to be positive and between 0° and 90°
- ζ_e: modulus of the latitude of the earth station
- δ: difference in longitude from the earth station to a point on the edge of the orbital shell of the constellation
- $\psi(\delta)$: great-circle arc between the earth station and a point on the surface of the Earth directly below the point on the edge of the orbital shell of the constellation
- $\alpha(\delta)$: azimuth from the earth station to a point on the edge of the orbital shell
- $\alpha_0(\delta)$: the principal azimuth, an azimuth between 0° and 180°, from an earth station to a point on the edge of the orbital shell

$\varepsilon_V(\delta)$: elevation angle from the earth station to a point on the edge of the orbital shell

K_I: orbit radius/Earth radius for the lowest altitude satellite in the constellation (Earth radius = 6 378.14 km)

$\psi_m = \arccos(1/K_1)$.

All arcs mentioned above are in degrees.

For any latitude on the surface of the Earth, the azimuth for which the minimum elevation angle to a satellite can be greater than zero, and the corresponding elevation angles, may be determined by implementing the calculations under the following case(s). No more than two of these cases will be applicable for any latitude. For situations not specifically addressed in the following cases, no satellite is visible at elevation angles at or below 90° on any azimuth.

Case 1: For: $\zeta_e \leq i_s - \psi_m$

For this case, a satellite may be visible to the horizon for all azimuths about the earth station ($\varepsilon_V = 0$).

Case 2: For: $i_s - \psi_m < \zeta_e \leq \arcsin(\sin i_s \cos \psi_m)$

For this case, the azimuth angles and elevation are developed parametrically by choosing a set of values of δ, uniformly spaced on the interval 0 to δ_1, and applying equations (4-1) to (4-4). For this purpose the spacing between values is not to exceed 1.0°, and the end points are to be included.

$$\delta_1 = \arccos\left[\frac{\cos\psi_m - \sin\zeta_e \sin i_s}{\cos\zeta_e \cos i_s}\right]$$

At any principal azimuth ($\alpha_0(\delta)$) that is not included in the set, the minimum elevation angle is zero ($\varepsilon_V = 0$), except for azimuths where Case 6 additionally applies.

Case 3: For: $\arcsin(\sin i_s \cos \psi_m) < \zeta_e < i_s$, and $\zeta_e < 180 - \psi_m - i_s$

For this case, the azimuth angles and elevation are developed parametrically by choosing a set of values of δ, uniformly spaced on the interval 0 to δ_2, and applying equations (4-1) to (4-4). For this purpose the spacing between values is not to exceed 1.0°, and the end points are to be included.

$$\delta_2 = 2\arctan\left[\frac{\sqrt{\sin^2\psi_m - \cos^2 i_s \ \sin^2\delta_1}}{\sin\zeta_e \ \cos i_s \ \sin\delta_1}\right] - \delta_1$$

At any principal azimuth ($\alpha_0(\delta)$) that is not included in the set, the minimum elevation angle is zero ($\varepsilon_V = 0$), except for azimuths where Case 6 additionally applies.

Case 4: For: $i_s \leq \zeta_e < i_s + \psi_m$, and $\zeta_e < 180 - i_s - \psi_m$

For this case, the minimum elevation angle is given explicitly in terms of the principal azimuth angle α_0, as follows:

$$\varepsilon_V = \begin{cases} 90 & \text{for} \quad 0 \leq \alpha_0 < \alpha_2 \\ 0 & \text{for} \quad \alpha_2 \leq \alpha_0 \leq 180 \end{cases}$$

where

$$\alpha_2 = \arccos\left[\frac{\sin i_s - \cos\psi_m \sin\zeta_e}{\sin\psi_m \cos\zeta_e}\right]$$

Note that a minimum elevation angle of 90° in this formulation indicates that no satellite is visible at elevation angles at or below 90° on these azimuths. Furthermore, within the range of principal azimuths where the minimum elevation angle is zero, Case 6 may additionally apply.

Case 5: For $180 - i_s - \psi_m \leq \zeta_e \leq 90$

For this case, a satellite may be visible to the horizon for all azimuths about the earth station $(\varepsilon_V = 0)$.

Case 6: For $\zeta_e < \psi_m - i_s$

This case may occur additionally with Case 2, Case 3 or Case 4 and a satellite may be visible only above a minimum elevation angle for other principal azimuths.

For this case, the other principal azimuths and the corresponding elevation angles are developed parametrically by choosing a set of values of δ, uniformly spaced on the interval 0 to δ_3, and applying equations (4-1) to (4-4) with i_s replaced by $-i_s$. For this purpose the spacing between values is not to exceed 1.0° and the end points are to be included.

$$\delta_3 = \arccos\left[\frac{\cos\psi_m + \sin\zeta_e \sin i_s}{\cos\zeta_e \cos i_s}\right]$$

1.2 Determination of minimum and maximum horizon gain from the minimum visible elevation angle profile

The horizon gain of the earth station antenna is determined from the profile of values of the minimum composite elevation angle (ε_c). At any azimuth, the minimum composite elevation angle is the greater of the minimum satellite visibility elevation angle at that azimuth (ε_V) and the minimum elevation angle for the earth station (ε_{sys}). The following procedure may be used to determine the maximum and minimum values of horizon antenna gain for each azimuth under consideration.

The following equation may be used to determine the angular separation between the horizon profile, at an azimuth angle α and horizon elevation angle ε_h, and a point on the profile of the minimum composite elevation angle, where the minimum composite elevation angle is ε_c at an azimuth angle of α_c:

$$\varphi(\alpha, \alpha_c) = \arccos\left[\sin \varepsilon_h(\alpha) \sin(\varepsilon_c(\alpha_c)) + \cos \varepsilon_h(\alpha) \cos(\varepsilon_c(\alpha_c)) \cos(\alpha - \alpha_c)\right] \qquad (4\text{-}5)$$

where:

α: azimuth of the direction under consideration

$\varepsilon_h(\alpha)$: elevation angle of the horizon at the azimuth under consideration, α

$\varepsilon_c(\alpha_c)$: minimum composite elevation angle at the azimuth, α_c

α_c: azimuth corresponding to ε_c.

The minimum value of the separation angle φ_{min}, for the azimuth under consideration, is determined by finding the minimum value of $\varphi(\alpha, \alpha_c)$ for any azimuth α_c, and the maximum value, φ_{max}, is determined by finding the maximum value of $\varphi(\alpha, \alpha_c)$ for any azimuth α_c. The azimuth angles (α) are usually taken in increments of 5°; however, to accurately determine the minimum separation angle, the values of the minimum composite elevation angle, ε_c, need to be determined for a spacing of 1° or less in the azimuth α_c. Where the procedures in § 1.1 of this Annex do not provide a profile of minimum composite elevation angle with a close enough spacing in azimuth angles, linear interpolation may be used to develop the necessary intermediate values. The maximum and minimum horizon antenna gains, G_{max} and G_{min}, to be used in the equations of § 2.2 of the main body of this Appendix for the azimuth under consideration are obtained by applying the off-axis angles, φ_{min} and φ_{max}, respectively, in the earth station antenna pattern. If the earth station antenna pattern is not known then the antenna pattern in § 3 of Annex 3 is used. In many cases, φ_{max} will be large enough on all azimuths so that G_{min} will be equal to the minimum gain of the antenna pattern at all azimuths.

ANNEX 5

Determination of the coordination area for a transmitting earth station with respect to receiving earth stations operating with geostationary space stations in bidirectionally allocated frequency bands

1 Introduction

The propagation mode (1) coordination area of a transmitting earth station with respect to unknown receiving earth stations operating with geostationary space stations requires the determination of the horizon gain of the antenna of the receiving earth station at each azimuth of the transmitting earth station. Different methods then need to be applied to determine the coordination area of the coordinating earth station, depending on whether it operates with geostationary or non-geostationary space stations. When both the coordinating earth station and the unknown receiving earth stations operate with geostationary space stations, it is also necessary to determine a propagation mode (2) coordination contour.

The coordination area of a transmitting earth station, with respect to unknown receiving earth stations that operate to non-geostationary space stations, can be determined by minor modifications to the methods applicable to the determination of coordination area of transmitting earth stations with respect to terrestrial stations. (See § 3.2.1 and § 3.2.3 of the main body of the Appendix.)

2 Determination of the bidirectional coordination contour for propagation mode (1)

For a transmitting earth station operating in a frequency band that is also allocated for bidirectional use by receiving earth stations operating with geostationary space stations, further development of the procedures in Annex 3 is needed. It is necessary to determine the horizon gain of the unknown receiving earth station, the horizon gain to be used at each azimuth at the coordinating (transmitting) earth station, for the determination of the bidirectional coordination area.

2.1 Calculation of horizon gain for unknown receiving earth stations operating with geostationary space stations

The value of G_r, the horizon gain of the receiving earth station, for each azimuth (α) at the transmitting earth station is found by the following steps:

1) The receiving earth station may be operating with any satellite in the geostationary orbit above a minimum elevation angle, (ε_{min}), contained in Table 9 in Annex 7. The maximum difference in longitude (δ_b, in degrees) between the receiving earth station and its associated space station occurs at this minimum elevation angle (ε_{min}) and is given by:

$$\delta_b = \arccos\left(\frac{\sin\left(\varepsilon_{min} + \arcsin\left(\frac{\cos(\varepsilon_{min})}{K}\right)\right)}{\cos(\zeta)}\right) \tag{5-1}$$

where:

ζ: latitude of the receiving earth station, which is assumed to be the same as the transmitting earth station

K: ratio of the radius of the satellite orbit to the radius of the Earth, equal to 6.62.

2) For each azimuth (α) at the transmitting earth station:

- determine the azimuth α_r from the receiving earth station to the transmitting earth station:

$$\alpha_r = \alpha + 180° \quad \text{for } \alpha < 180$$

$$\alpha_r = \alpha - 180° \quad \text{for } \alpha \geq 180$$

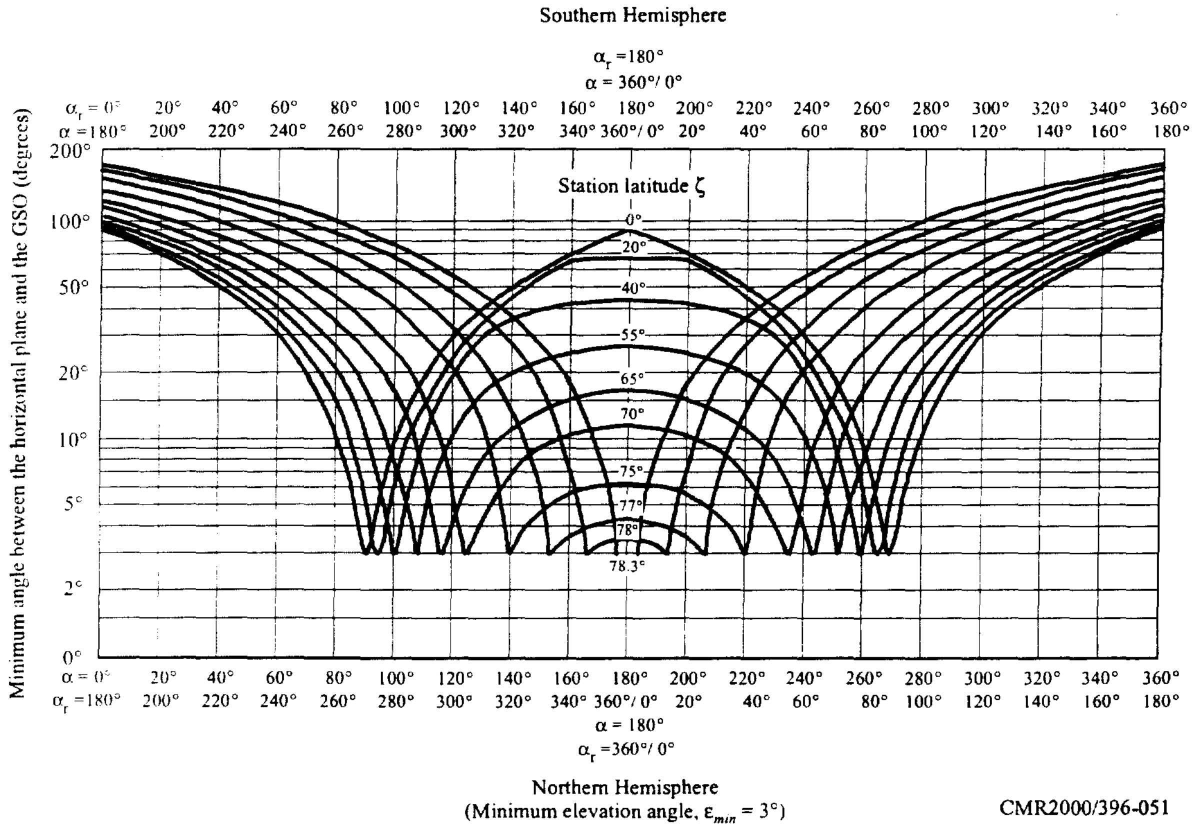
- for each azimuth α_r, determine the minimum angular separation, $\varphi(\alpha_r)$, between the receiving earth station main beam axis and the horizon at this azimuth using Case 1 in § 2 of Annex 3. For this evaluation, $\varphi(\alpha_r)$ is the minimum value of $\varphi(\alpha_r, 0, \delta_0)$, where the values of δ_0 are between $-\delta_b$ and $+\delta_b$ in steps of 1° or less, making sure to include the end points.

The minimum angular separation, $\varphi(\alpha_r)$, may be used with the gain pattern in § 3 of Annex 3 to determine the horizon gain for this azimuth (α), unless a different gain pattern is referenced in Table 9 of Annex 7.

Figure 5-1 shows plots of the minimum angular separation between the horizon at zero degrees elevation on an azimuth α_r and a satellite on the geostationary orbit at an elevation above 3°. Plots are shown for a set of values of the station latitude (ζ), which is assumed to be the same for both transmitting and receiving earth stations. Figure 5-1 also provides a scale showing the corresponding azimuth (α) of the transmitting earth station.

FIGURE 5-1

Illustration of minimum angular distance between points on the geostationary-satellite orbit (GSO) and the horizontal plane



Further information and an example may be found in the latest version of Recommendation ITU-R SM.1448.

3 Determination of the bidirectional rain scatter contour

The procedure for the determination of the bidirectional rain scatter area, as described in § 3.1.2 of the main body of this Appendix, is as follows:

The horizontal distance d_s (km) from the coordinating earth station to the point at which the main beam axis attains the rain height h_R is calculated by:

$$d_s = 8\,500\left(\sqrt{\tan^2 \varepsilon_s + h_R / 4\,250} - \tan \varepsilon_s\right) \text{ km} \qquad (5\text{-}2)$$

where the rain height, h_R, can be determined from equations (2-13) or (2-14) in Annex 2 and ε_s is the minimum elevation angle of the transmitting earth station.

The maximum calculation distance, d_{emax}, to be used in the determination of the propagation mode (2) contour, for the case of a coordinating earth station operating in bidirectionally allocated frequency bands, is dependent on the rain height. It is the greater distance determined from:

$$d_{emax} = 130.4\sqrt{h_R} \text{ km or } d_{min}$$

where the minimum coordination distance, d_{min}, is given in § 4.2 of the main body of this Appendix.

The point, at the distance d_s from the earth station, on the azimuth α_s of the coordinating earth station's main beam axis, is the geographic point immediately below the main beam axis intersection with the rain height, and is the reference point from which the maximum calculation distance d_{emax} is determined (see Figure 5-2).

If the maximum calculation distance, d_{emax}, is greater than the minimum coordination distance, d_{min}, then calculate the maximum latitude at which a receiving earth station may operate with a geostationary satellite with a minimum elevation angle ε_{min}:

$$\zeta_{max} = \arccos\left[\frac{\cos(\varepsilon_{min})}{K}\right] - \varepsilon_{min} \tag{5-3}$$

where

ε_{min}: given in Table 9 of Annex 7

K: ratio of the radius of the satellite orbit to the radius of the Earth, equal to 6.62.

If the coordinating earth station latitude in the northern hemisphere is greater than ζ_{max}, or if the coordinating earth station latitude in the southern hemisphere is less than $-\zeta_{max}$ or $-71°$, then the rain scatter contour is a circle of radius d_{min}, centred on the transmitting earth station.

For all other cases, the coordination area is developed by the following procedure:

Step 1: The unknown receiving earth station is assumed to be operating with a satellite at the minimum elevation angle ε_{min}. It is also assumed that the receiving earth station is relatively close to the coordinating earth station in geometric terms and hence a plane geometry approximation can be applied within the coordination area. If the receiving earth station's main beam axis passes through the intersection of the coordinating earth station's main beam axis with the rain height, the azimuths from the point on the ground immediately below this intersection to the possible locations of a receiving earth station are given by:

$$\alpha_{w1} = \arccos\left[\frac{\tan\zeta}{\tan\zeta_{max}}\right]$$

and

$$\alpha_{w2} = 360 - \alpha_{w1}$$

where:

ζ is the latitude of the transmitting earth station.

Step 2: Mark on a map of an appropriate scale the coordinating earth station's location and draw from this location a line of distance, d_s, along the azimuth, α_s, to the point below the coordinating earth station's main beam axis intersection with the rain height.

Step 3: From the main beam axis intersection point in Step 2, mark on the map the distance, d_{emax}, along the two azimuths, α_{w2} and α_{w1}, and on each azimuth at the distance, d_{emax}, draw two equal distance arcs of width 3° clockwise and counter-clockwise. The two arcs, each having a total width of 6°, are the first boundary elements of the bidirectional rain scatter area.

Step 4: Mark a circle of radius equal to the minimum coordination distance, d_{min}, around the coordinating earth station's location, and then draw straight lines from the northern edges of the two arc segments tangential to the northern rim of the circle, and from the southern edges of the two arc segments tangential to the southern rim of the circle.

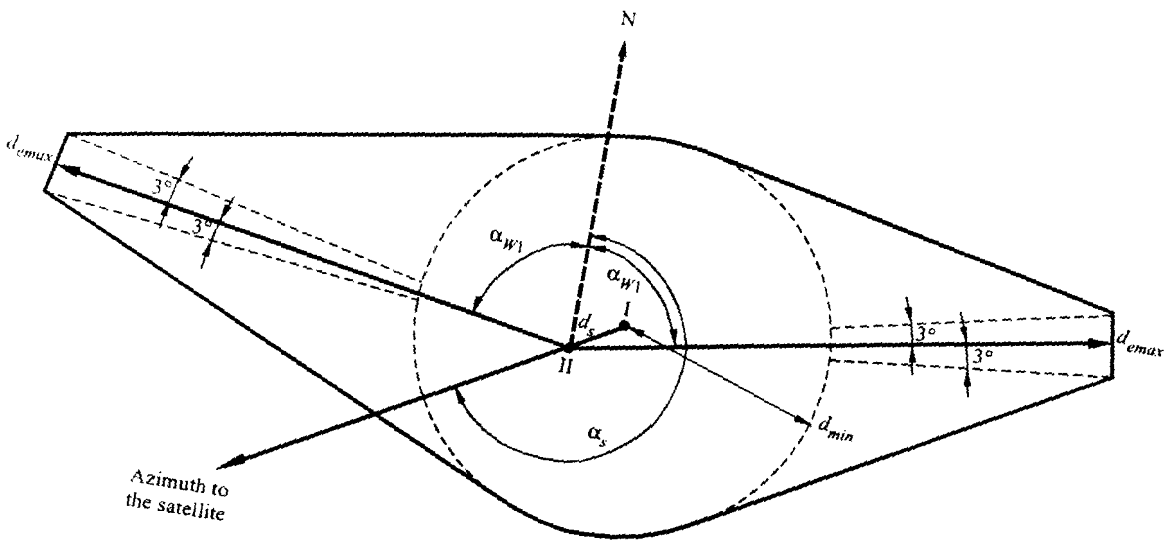
The area bounded by the two 6° wide arcs, the four straight lines, and the circular sections (of which there is always at least one) between the two northern and the two southern tangent points with the straight lines, constitutes the bidirectional rain scatter area.

Figure 5-2 illustrates the construction of the bidirectional rain scatter area for a coordinating earth station. (The resulting rain scatter area contains the possible loci of all receiving earth station locations from which a beam path towards the geostationary-satellite orbit will intersect the main beam of the transmitting earth station antenna.)

FIGURE 5-2

Example of the bidirectional rain scatter area

(not to scale)



I: location of the transmitting earth station

II: point where the earth station antenna main-beam axis reaches the altitude h_R

Assumptions:

$\zeta = 40°$ N

$\varepsilon_s = 10°$

$\alpha_s = 254°$

CMR2000/396-052M

ANNEX 6

Supplementary and auxiliary contours

1 Introduction

The material found in this Annex is intended to assist administrations in bilateral discussions.

2 Supplementary contours

The coordination area is determined with respect to the type of terrestrial station (or, in a frequency band with a bidirectional space allocation, an earth station operating in the opposite direction of transmission) that would yield the largest coordination distances. Therefore, in the case of terrestrial services, fixed stations using tropospheric scatter have been assumed to be operating in frequency bands that may typically be used by such radiocommunication systems; and fixed stations operating in line-of-sight configurations and using analogue modulation have been assumed to be operating in other frequency bands. However, other radiocommunication systems (e.g. other terrestrial stations), that typically have lower antenna gains, or otherwise less stringent system parameters, than those on which the coordination area is based, may also operate in the same frequency range. Therefore, it is possible for the administration seeking coordination to identify a supplementary contour using either the methods in § 2 or § 3 of the main body of this Appendix, where they are applicable, or other agreed methods. Subject to bilateral agreement between administrations, these supplementary contours can assume the role of the coordination contour for an alternative type of radio system in the same service or another radiocommunication service.

When a supplementary contour is to be developed for other types of systems, for example digital fixed systems, the necessary system parameters may be found in one of the adjacent columns in Tables 7, 8 and 9 of Annex 7. If no suitable system parameters are available then the value of the permissible interference power ($P_r(p)$) may be calculated using equation (7-1) of § 2 in Annex 7.

In addition, supplementary contours may be prepared by the administration seeking coordination in order to define smaller areas, based on more detailed methods, for consideration when agreed bilaterally between the concerned administrations. These contours can be a useful aid for the rapid exclusion of terrestrial stations or earth stations from further consideration. For earth stations operating with non-geostationary space stations, supplementary contours may be generated using the method in § 4 of this Annex.

Supplementary contours may comprise propagation mode (1) interference paths and, depending on the sharing scenario, propagation mode (2) interference paths. In addition, the propagation mode (1) element of a supplementary contour may, if appropriate for the radiocommunication service, utilize the same level of correction factor (see § 4.4 of the main body of this Appendix) that was applied in the determination of the coordination contour. However, all parts of each supplementary contour must fall on or between the contour defined by the minimum coordination distance and the corresponding propagation mode (1) or propagation mode (2) main contour.

3 Auxiliary contours

Practical experience has shown that, in many cases, the separation distance required for the coordinating earth station, on any azimuth, can in fact be substantially less than the coordination distance, since the worst-case assumptions do not apply to every terrestrial station or earth station. There are two main mechanisms that contribute to such a difference between the separation distance and the coordination distance:

- the terrestrial station antenna gain (or e.i.r.p.), or receiving earth station antenna gain, in the direction of the coordinating earth station is less than that assumed in calculating the coordination contour;
- appropriate allowance can be made, for example, for the effects of site shielding not included in the coordination distance calculations.

Auxiliary contours must use the same method as that used to determine the corresponding main or supplementary contour. In addition, all parts of each auxiliary contour must fall on or between the contour defined by the minimum coordination distance and the corresponding main or supplementary contour. Auxiliary contours may assist in eliminating from detailed coordination terrestrial stations or earth stations that are located in the coordination area and hence have been identified as potentially affected by the coordinating earth station. Any terrestrial station or earth station that lies outside an auxiliary contour and has an antenna gain towards the coordinating earth station that is less than the gain represented by the relevant auxiliary contour need not be considered further as a significant source, or subject, of interference.

3.1 Auxiliary contours for propagation mode (1)

Propagation mode (1) auxiliary contours are calculated with values for the propagation mode (1) minimum required loss in equation (22) in § 4.4 of the main body of this Appendix that are progressively reduced by, for example, 5, 10, 15, 20 dB, etc., below the value derived from the parameters assumed in Tables 7, 8 and 9 of Annex 7 for the corresponding main or supplementary propagation mode (1) contour, until the minimum coordination distance is reached. Propagation mode (1) auxiliary contour distances are calculated without the correction factor (see § 4.4 of the main body of this Appendix), and hence could be larger, on any azimuth, than the corresponding main, or supplementary, propagation mode (1) distance. To prevent this, in those cases where a correction factor applies to the main or supplementary contour, the maximum propagation mode (1) auxiliary contour distance on any azimuth is limited to the corresponding main or supplementary propagation mode (1) distance. In effect this means that the correction factor will limit the possible range of auxiliary contour values so that only those auxiliary contours with values greater than the applied correction factor will be shown within the main or supplementary contour (see Figure 6-1). For example, if the value of correction factor applicable to the propagation mode (1) main or supplementary contour is 10 dB, then the first auxiliary contour drawn would be for a reduction in minimum required loss of 5 dB and hence the auxiliary contour value would be −15 dB (by convention, auxiliary contours are shown as negative quantities as they represent a reduction in the terrestrial, or receiving earth station, antenna gain, or the terrestrial station e.i.r.p.).

Propagation mode (2) interference effects may still need to be considered even if propagation mode (1) interference effects have been eliminated from detailed coordination, as the propagation models are based on different interference mechanisms.